DEPARTMENT OF TRANSPORTATION

Slope Stabilization and Repair Solutions for Local Government Engineers

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June 2017

Research Project
Final Report 2017-17

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Slope Stabilization and Repair Solutions for Local Government Engineers

FINAL REPORT

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c'	Effective cohesion
Co.	County
CSAH	County state aid highway
DCP	Dynamic cone penetrometer
DNR	Department of Natural Resources
EPS	Expanded polystyrene (geofoam)
eqn	Equation
FHWA	Federal Highway Administration
FS	Factor of safety
H	Slope height
kN	Kilonewton
kPa	Kilopascal
LEM	Limit equilibrium method
m	Meter
MN	Minnesota
MnDOT	Minnesota Department of Transportation
MSE	Mechanically stabilized earth
N_{60}	Field corrected blow count for penetration testing
pcf	Pounds per cubic foot
psf	Pounds per square foot
SPT	Standard penetration test
S_u	Undrained shear strength
tsf	Tons per square foot
u	Porewater pressure
USCS	Unified Soil Classification System
UTM	Universal Transverse Mercator coordinate system
β	Slope inclination angle
γ	Soil unit weight
γ_w	Unit weight of water
σ'	Effective normal stress
τ	Shear stress
ϕ'	Effective friction angle
°	Degrees

EXECUTIVE SUMMARY

The purpose of this project is to create a user-friendly guide focusing on locally maintained slopes requiring reoccurring maintenance in Minnesota. This study addresses the need to provide a consistent, logical approach to slope stabilization that is founded in geotechnical research and experience and applies to common slope failures. Authors used input from Minnesota county engineers, case studies from site investigations throughout the state, and a parametric study of slope stability modeling parameters to develop stabilization recommendations.

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The target audience of the guide is county or local municipal engineers who do not have specialized geotechnical engineering experience. The research does not address slope stability issues of the scale that require local municipalities to hire geotechnical engineering specialists. Authors intend the deliverable to assist with efficient stabilization of common recurring slope failures along roadways

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CHAPTER 1: INTRODUCTION

1.1 PURPOSE AND NEED FOR RESEARCH

The purpose of this study is to determine effective methods of stabilizing slopes along Minnesota's locally maintained roads and recommend slope stabilization methods for common site conditions. The project recommends simple, effective methods of stabilizing at-risk sites and repair options for common, recurring slope failures. There is currently no guide for public works engineers to stabilize slopes of the scale typically seen along locally maintained roadways. Therefore, slope failures can block roads, pose safety hazards, and introduce preventable maintenance costs. While there is no single stabilization method appropriate for all situations, several methods have proven effective. Researchers explored stabilization methods and produced a deliverable to summarize findings. The deliverable is a guide to slope stabilization for local government engineers.

1.2 RESEARCH OUTLINE AND PROJECT SCOPE

This project combines site investigations, laboratory testing, and Limit Equilibrium Method (LEM) modeling to characterize recent slope failures in Minnesota. The project team followed a four-step approach to produce the final deliverable. In Task 1, researchers identified and initially characterized slopes for further analysis via a survey sent to each county engineering department in the state. Respondents identified stabilization methods, and sites at which researchers could conduct field investigations to produce case studies. In Task 2, the team identified and researched various stabilization methods in a literature review. In Task 3, laboratory testing was conducted to more accurately characterize soil collected from slopes of interest. In a parametric study, LEM models were developed to investigate each slope stabilization method's effect. In Task 4, researchers summarized the project's findings and presented recommendations in a slope stabilization guide for local government engineers.

This study addresses the need to provide a consistent, logical approach to slope stabilization that is founded in geotechnical research and experience, and applies to common slope failures. The deliverable was developed with resources typically not used by all county engineering and maintenance departments, such as soils lab testing, LEM modeling, and geotechnical analysis. The target audience of this research and final deliverable is county or local municipal engineers that do not have specialized geotechnical engineering experience. The research does not address slope stability issues of the scale requiring local municipalities to hire geotechnical engineering specialists. This project provides an example of a parametric study for future engineering research, and makes recommendations for local government engineers to improve the stability of roadway embankments, minimize slope failure and associated damage, and decrease preventative maintenance cost with efficient stabilization methods.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

To provide slope stabilization recommendations, researchers needed to establish a background understanding of slope stability and stabilization methods. Authors conducted a literature review and identified stabilization approaches to consider in research.

2.1 SLOPE STABILITY OVERVIEW

Slope stability is typically quantified with a factor of safety (FS). Stabilizing a slope involves increasing the FS. The FS is the ratio of shear strength to the required shear strength for equilibrium along a given potential failure surface, as shown in Equation 1.

(Eqn. 1) $$\text{Factor of Saftey} = \frac{\textit{in situ}\ \text{shear strength}}{\text{shear stress required for sliding}}$$

Fundamentally, there are two ways to increase the FS and increase slope stability: introduce more stabilizing forces (increase capacity) or limit driving forces (decrease demand). Academic research, standard engineering practice, and worldwide experience have produced many slope stabilization methods; most fit into four categories: controlling groundwater with drainage, using surface cover, excavating and regrading, and adding reinforcing support structures. To determine effective ways to stabilize the slopes encountered by public works engineers, a literature review was conducted. The research team analyzed common stabilization techniques.

2.2 CONTROLLING WATER

Water has a negative effect on soil's ability to resist shearing, which leads to slope failure. An increase in pore pressure leads to a decrease in effective stress (σ'). Because σ' governs the soil's strength characteristics, the presence of water leads to decreased soil shear strength. Controlling groundwater in the slope area is a fundamental way to increase the resistance to shear failure.

Drainage is a basic way to minimize the amount of water present in the slope. Drains provide a path for water to flow away from the potential slide area and increase shear strength. Surface drains, trenches, horizontal drains, and drainage wells are some methods to control water in the slope area. Surface drains limit the amount of infiltration into slope material. Trenches, drains, and wells are used to divert water after infiltration; their construction varies greatly by project type. Rahardjo et al. (2003) describes several drainage features designed to increase slope stability. Local conditions often govern material selection.

Typical drainage pipes used in construction vary in material, size, and installation method. Drainage pipes all have a common goal: remove water that has already infiltrated into the potential slide area. Typically surrounded with a free-draining filter media, these pipe drains help transport water from the slope. Horizontal pipe drains can be installed from the slope face, without excavation material. Installing the drains with a slight slope allows gravity to drain water from the slope material into a collection channel. Figure 1 shows a simple example of drainage features. Often, multiple drainage features used together can be most effective.

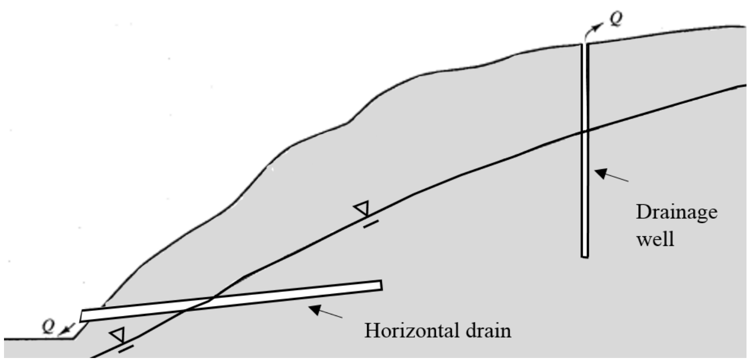


Figure 1: Drainage features used to remove water from a slope (adapted from Coduto et al., 2011)

Drainage trenches are a method of controlling water that does not require additional specialty subcontractors. Digging an open channel to divert water flow can be a simple and effective solution to excess groundwater concerns. Trenches are good temporary solutions for site drainage during construction. If the excavation is backfilled with a free-draining material, placing a perforated pipe in the trench will create a permanent drainage feature, as shown in Figure 2.

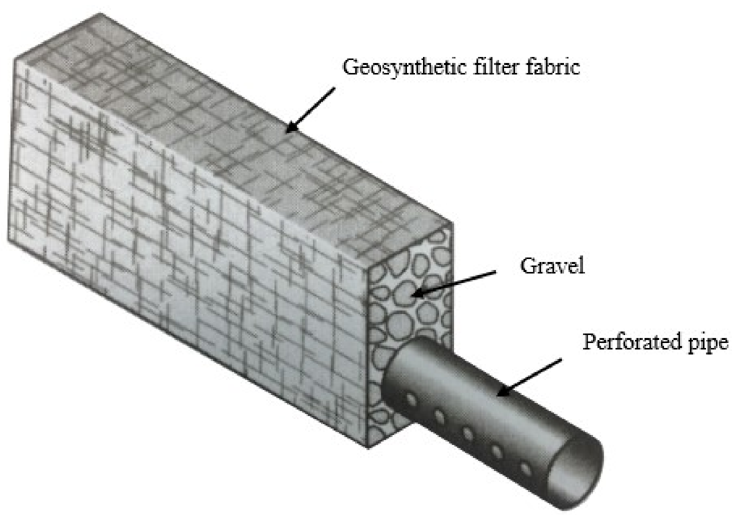


Figure 2: Example of perforated pipe drain usage (from Coduto et al., 2011)

When construction is necessary in areas that are affected by groundwater, a more involved method is required. Dewatering is a method of groundwater control that effectively lowers the groundwater table. This is typically performed with a pump system. Dewatering can involve extensive work and cost, and is typically outside the scope of recurring slope stability repairs.

Dimensions, spacing, and layout of drainage features are often affected by site conditions and contractor experience. There is no single answer to stabilizing slopes with drainage. A general suggestion is to place drains close to the failure zone, and near the steepest angle exhibited by the slope (Stanic, 1984).   Drains placed near the toe generally remove the most water.

2.3 SURFACE COVER

Another method of stabilizing slopes is surface cover. Appropriate soil cover can prevent drainage-related instability by diverting water, limit the effects of erosion, and provide stabilizing forces for the upper layer of a slope. Vegetative cover, rip-rap, suitable fill, and buttressing are common approaches to slope stabilization by ground cover.

Using vegetation as ground cover is common and an easily implemented method. Grass and other vegetation protect the soil in the potential slide zone from the impact of rainwater and surface runoff. Operstein et al. (2000) present the effect of plant roots on soil shear strength with research involving lab testing of roots and analysis of mechanical properties. Each vegetated soil had a shear strength greater than that of the soil without roots. Plant roots remove water from the soil, limiting the effect of pore pressure and reducing the chance of surficial failures. Roots also provide mechanical reinforcement at the surface.

Another advantage of vegetative cover is ease of installation. No specialty equipment is required. Grass seed can be easily placed at low labor cost, and material is readily available. Placing grass seed or other vegetation at the end of a slope repair project is common practice. Vegetative cover also decreases runoff from roadways. A site demonstrating steep slopes held in place with natural vegetative cover is shown in Figure 3.

Figure 3: Vegetative cover stabilizing a slope in Lac Qui Parle County, MN

Buttressing is placing a soil or rock mass against a slope face to add stabilizing force and decrease the overall slope height, as shown in Figure 4. Buttressing can be as simple as placing material against the slope. Temporary buttresses can provide cover and stabilizing support for construction projects.

Figure 4: Basic buttress layout

Placing coarse gravel or cobble rip-rap on the slope face can provide surficial protection and limit the effect of erosion, but adds weight. Figure 5 shows a large slope entirely covered with quarried cobble. Rip-rap placement is labor-intensive and generally has a higher cost than earthwork buttressing, but can protect the slope from erosion. Using high-flow concrete (shotcrete) is another option with similar cover advantages. Slope cover methods can add weight and actually decrease global stability; cover is typically an erosion-control method.

Figure 5: Slope covered with rip-rap in St. Louis County, MN

2.4 DECREASING LOAD / REGRADING

The two fundamental ways to increase the FS for a slope are increasing resisting forces and decreasing the load. When possible, altering slope geometry to minimize the forces driving failure can stabilize the slope. If spatial concerns such as jobsite and right-of-way boundaries are not an issue, decreasing the slope angle is an effective option. Another way to decrease the driving forces is to remove any load or surcharge from the top of the slope, decreasing weight. Cornforth (2005) describes a case study of slopes surrounding the Pelton Dam in central Oregon. The slopes were repaired with a lower slope angle and significant decrease in slope failure was observed.

Using a lightweight fill can decrease overall slope weight and lower driving forces. Abramson et al. (2002) identifies expanded shale, shredded tires, encapsulated sawdust, seashells, and polystyrene foam as some examples of lightweight fill. Material choice is largely dependent on local availability and transportation costs. Lightweight fill is a design consideration for new slope construction and a material option for slope repair.

Free draining compacted fill has ideal properties as a slope material. Replacing the potential slide material with this engineered fill minimizes uncertainty in ground conditions and eliminates factors that lead to slope instability. Removing the *in situ* soil and placing fill also allows the design team to control the geometry of the slope. However, material and budget considerations can make this method impractical. In cases where the remove-and-replace option is appropriate, proper fill selection in design improves *in situ* strength and drainage properties. On one such project in Murray County, MN, a convenient source of fill was located near the site. This made the remove-and-replace method feasible. The slope reconstruction process is shown in Figure 6.

Figure 6: Slope reconstruction project in Murray County, MN (from Murray Co. Highway Dept.)

Benching, or excavating flat cutouts periodically along the slope, can be used to stabilize temporary excavations and permanent embankments. Benching, also called terracing, allows the use of a steeper overall slope. Local building codes and safety committees are sources for benching dimension guidelines. The benches along an excavation face provide a convenient flat surface for workers and equipment. Drainage features can also be installed on benches, increasing the long-term stability. An example of a benched excavation is shown in Figure 7.

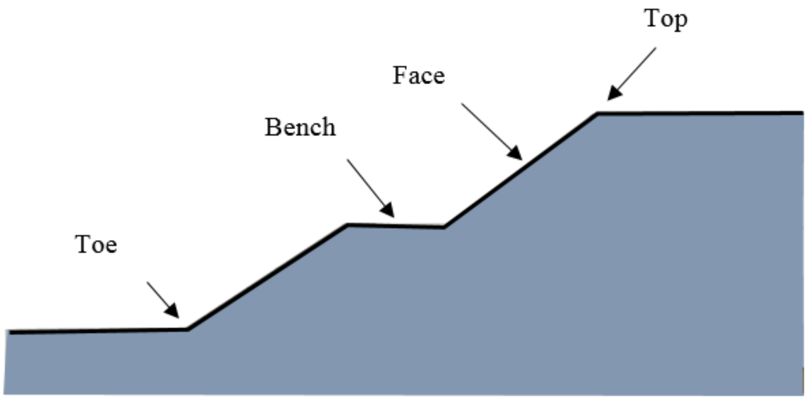


Figure 7: Example benched slope (adapted from Coduto et al., 2011)

2.5 REINFORCING SUPPORT STRUCTURES

The installation of reinforcing structures increases resisting forces, and therefore increases FS. Retaining walls, soil nailing, ground anchors or tiebacks, and mechanically stabilized earth (MSE) walls are examples of stabilizing structures. Most reinforcing structures require specialized experience and are likely more suitable solutions for large projects. There are standardized design approaches for many stabilizing structures. Although reinforcing structures are an expensive option, they are sometimes necessary to stabilize slopes.

Using a wall to hold back soil is applicable from small landscape projects to full-scale highway embankment stabilization. Retaining walls can be used in situations where space is an issue. A well-designed and constructed retaining wall can allow roadway design teams to work around severe grade changes presented by some highway projects, as demonstrated in Figure 8. The Federal Highway Administration (FHWA) is a source for design guidelines for retaining walls along roadways, such as Christopher et al. (2009). Retaining walls can be used to manage grade changes, keep salt, oil and other highway chemicals off the surrounding environment, and protect motorists from rocks, wildlife and other hazards that could enter the roadway.

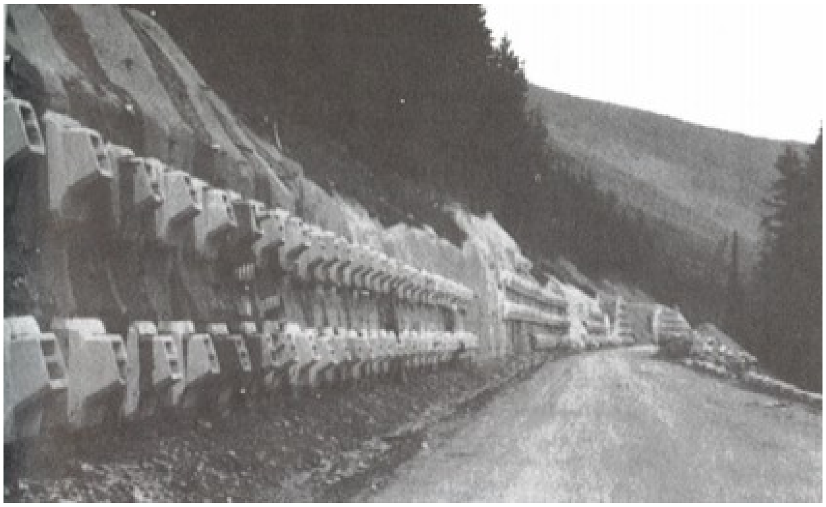


Figure 8: Retaining walls allow roads to be built on steep side slopes (from Abramson et al., 2002)

Soil nailing is another method using reinforcing structures. Generally, a pile, rod, or pipe is driven into the soil mass to provide a mechanical stabilization. This method is most effective when geotechnical modeling or analysis can approximate the failure surface, allowing the nails to be installed into stable soil. In some cases, cement grout is used to anchor the structure. The method also works in rock, when drilling and grouting create an anchor, or rock bolt. Figure 9 shows a sample soil nail design. Soil nails and rock bolts can be used in combination with other stabilization methods, such as surficial cover, as shown in Figure 10. Soil nails can also be used to support retaining walls as tieback anchors. Soil nailing typically requires a specialty contractor.

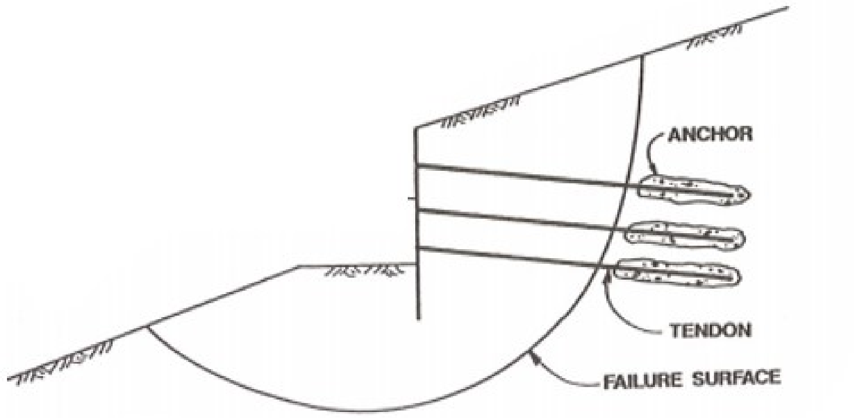


Figure 9: Soil nails extend past the failure surface to provide stability (from Abramson et al., 2002)

Figure 10: Rock bolts in combination with mesh cover in Washington County, MN

Soil nails, anchors, and tiebacks can be driven like foundation piles, or pre-drilled and grouted. Helical piles can be simply screwed into soil for placement. While helical pile installation is a specialty operation, it avoids the disruption and noise of driving. Support structures can also be installed by excavating a well or borehole, and filling with concrete or gravel fill to create a cast-in-place or stone columns. The "bore-and-fill" method is commonly approached like a rock anchor or structural tensile anchor. After boring through the soil mass to the stable soil, steel cables or tendons are placed in the borehole and tensioned. Concrete or grout is then placed to support the tendons. The bore-and-fill soil nail type is typically more effective than a driven pile, but much more design work is involved in determining tendon type, material, and length needed. Due to the large variety of structural support methods, each stabilization project requires individual design consideration.

Geosynthetic reinforcement is another stabilization option. The term "goetextile" is used to describe a permeable fabric. The term "geogrid" typically refers to a lattice-pattern synthetic that is placed between lifts of placed fill material. An example is shown in Figure 11. Geomembranes are another type of geosynthetic that can keep fines from pumping to the surface. Many other geosynthetic products are available with a variety of types and applications. Westfall (2014) describes how geogrids were used in combination with other methods to stabilize slopes along U.S. 50 in Nevada, near Lake Tahoe. The Nevada Department of Transportation hired engineering consultants and used proprietary designs, indicating that this specific method is likely not an in-house option for Minnesota county engineers. Geosynthetics are often chosen because of ease of installation, and work well in combination with other stabilization methods.

Figure 11: A worker anchors geogrid at the Lake Tahoe project (from Westfall, 2014)

Mechanically stabilized earth embankments are simply a combination of several methods already discussed. Generally more common in new construction, an embankment is constructed using prescribed fill placed in compacted lifts with geosynthetic reinforcement between layers. Fill is typically free-draining borrow material, unless the site has adequate *in situ* soil. Drainage features may also be installed. This embankment type stabilizes slopes, but is also generally expensive. The FHWA is a good source for design guidelines and standards for MSE walls and other structural reinforcement methods (Berg et al., 2009).

2.6 SUMMARY

There are many options for slope stabilization and repair. Method selection is site-specific. Managing groundwater and drainage can improve the shear strength in a potential slide area. Surface cover can protect the slope from water and erosion, and roots add stabilizing force to the soil. Excavation and re-grading decrease the forces that drive failure. Structural reinforcement features add direct supporting forces to slope material. The research produced an understanding of 12 general stabilization techniques. The stabilization methods and approaches that the investigation team researched are summarized in Table 1, along with a source for background material describing each method's application.

Table 1: Slope stabilization methods researched

Stabilization Method	**Source of Defining Example**
Drainage features	Cornforth (2005) Ch. 17
Dewatering	Coduto et al. (2011) Ch. 11
Vegetative cover	Abramson et al. (2002) Ch. 7
Buttressing / rip-rip cover	Abramson et al. (2002) Ch. 7
Geosynthetics	Gee (2015)
Lightweight fill	Abramson et al. (2002) Ch. 7
Remove and replace	Duncan and Wright (2005) Ch. 16
Re-grading and benching	Cornforth (2005) Ch. 15
Retaining walls	Cornforth (2005) Ch. 19
Soil nailing	Abramson et al. (2002) Ch. 7
Mechanically stabilized earth embankments	Abramson et al. (2002) Ch. 7

CHAPTER 3: METHODS

Researchers collected input for modeling through the initial survey and site investigations. Lab testing provided data for analysis, and a parametric study provided insight to the effectiveness of each method. Summarizing results led to recommendations in the deliverable.

3.1 LOCAL GOVERNMENT ENGINEER SURVEY

Ensuring that recommendations are practical for local government agencies was critical. Accordingly, authors developed a survey for Minnesota county engineers to determine slope stabilization methods for consideration. The survey asked engineers to identify slopes within their jurisdiction requiring reoccurring maintenance, successful and unsuccessful methods of maintaining those slopes, and share project details. Correspondence with survey respondents also allowed researchers to schedule site visits and develop case studies. The survey was sent to Minnesota county and maintenance engineers in September 2015; fourteen engineering departments responded. Respondents indicated a variety of successful stabilization methods, and an equally varied experience with unsuccessful methods. A copy of the survey and results summary is provided in Appendix A.

3.2 SITE INVESTIGATION PROCESS

Survey respondents identified case study sites in their respective jurisdictions. Figure 12 summarizes the site investigation locations. During site visits, researchers measured slope geometry with a field tape measure and surveying equipment, as shown in Figure 13. Investigators also determined soil type and strength properties. Vane shear test and pocket penetrometer results indicate the value of undrained shear strength (S_u) in tons per square foot (tsf).

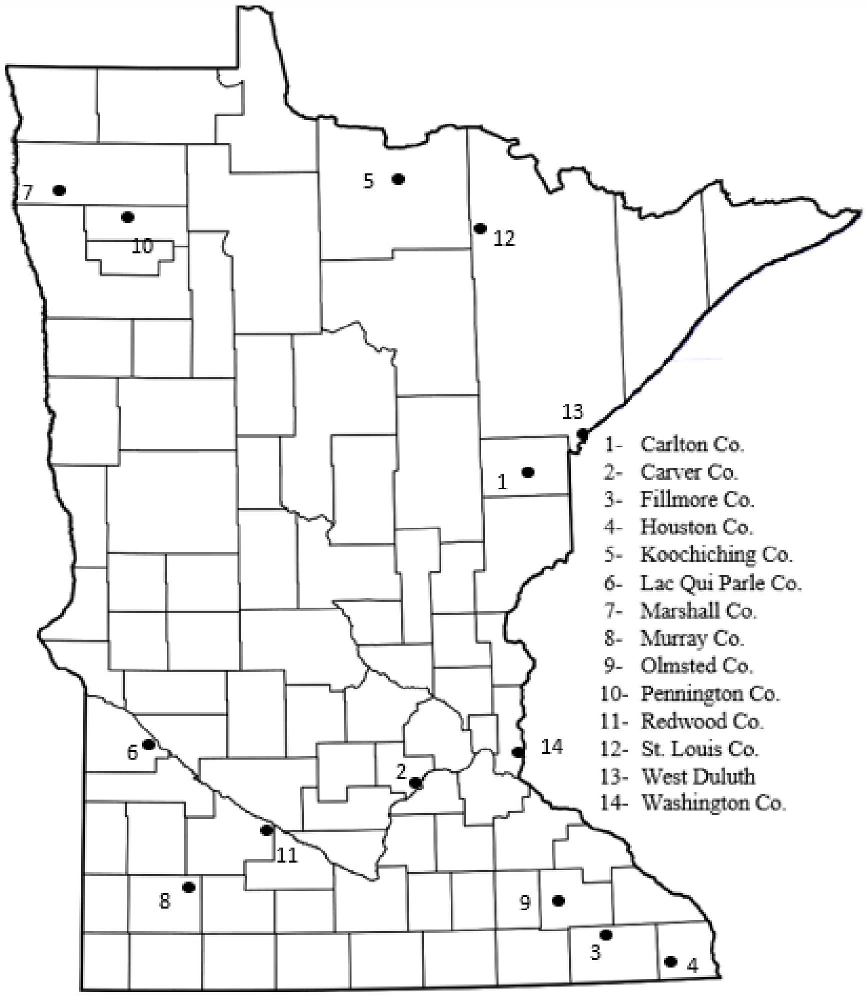


Figure 12: Site investigation locations

Figure 13: Field investigators used survey equipment to determine slope geometry

Soil was visually classified using samples collected with a hand auger. Soil was classified according to the Unified Soil Classification System (USCS). Where site investigation data was not available, *in situ* measurements of soil strength were collected using the pocket penetrometer and dynamic cone penetrometer (DCP). The DCP test results are comparable to standard penetration test (SPT) results. Researchers measured the amount of blows to advance a rod struck with a known weight a given distance into the soil. The DCP test is more easily implemented than full-scale geotechnical testing. The test is easy to include in a field investigation, and the most convenient way to directly measure *in situ* resistance to penetration. Testing was conducted in general accordance with *ASTM D7380 – 15*. Results can be correlated to SPT values, as shown in Figure 14. The value correlated to SPT blow counts is the field corrected SPT blow count, or N_{60}. Blow counts allowed investigators to estimate the *in situ* density and strength for replication in lab testing. DCP results are part of a comprehensive site assessment, and were not used to directly correlate strength values.

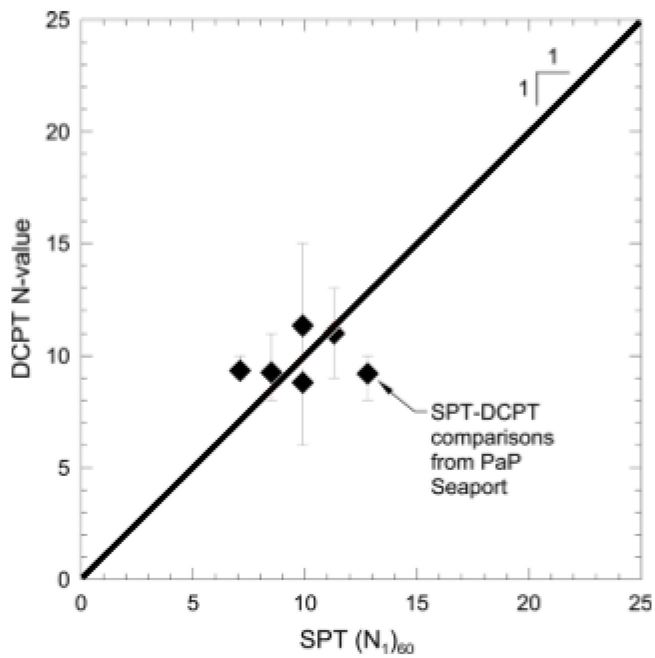


Figure 14: Correlation from DCP to SPT blow counts (from Green et al., 2011)

Photographs and field notes captured the site's cover, erosion potential, drainage, and ground water conditions. Ojakangas (2009) provided an overview of each site's geologic history, which was verified by a Minnesota Geological Society surficial geology map (Hobbs & Goebel, 1982). Depth to the ground water table was estimated using the Minnesota Department of Natural Resources (DNR) monitoring wells.

Researchers also noted the presence or absence of visible failure planes, and classified apparent failure types. Classification followed a FHWA design manual on soil embankments (Collin et al., 2001). Most commonly observed failures were creep failures and rotational slide failures. Examples are shown in

Figure 15. Creep slides are slow surficial failures involving gradual downhill movement of slope material. Visible displacement, or bio-indicators such as trees that grow crooked, are characteristics of creep movements. Seasonal freeze-thaw cycles and inadequate shear strength properties can cause creep failure. Rotational slide failure is generally characterized by a circular failure plane in cross section. This failure type typically leaves exposed soil, called the scarp. In some soil types, cracking at the surface can indicate the slope is nearing a rotational failure.

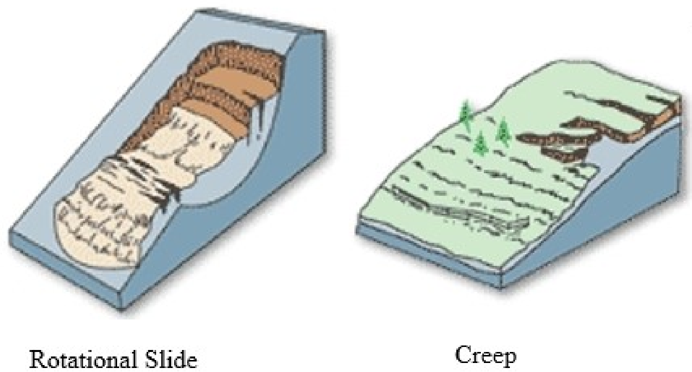


Figure 15: Examples of common slope failure types (from Varnes, 1978)

The goal of the site investigations was to compile a representative set of case studies for analysis and modeling. Appendix B provides supplementary information for each site visit including location details, soil properties and slope characteristics summaries, and geometry descriptions.

3.3 LABORATORY TESTING

Researchers determined soil strength properties using the direct shear test. Slope failures are examples of plane strain, and test specimens are tested and failed in the same way. This similarity in failure mechanism slope stability and failure modeling a good application of direct shear testing. The procedure was conducted in general accordance with *ASTM D3080-11*. The outcome of direct shear testing was values of shear strength parameters for each soil sample, particularly effective friction angle (φ') and effective cohesion (c'). Tests were conducted with the samples saturated to eliminate the effect of negative pore water pressure that may occur with partially-saturated samples.

Soil classification is a basic part of a geotechnical investigation. Many stabilization and construction method practices depend on soil type. Researchers conducted Atterberg Limit testing in general accordance with *ASTM D4318-10* to determine the plastic limit (PL) and liquid limit (LL) of each sample. The plasticity index (PI) is the difference between the PL and LL. *ASTM 2487-11* describes how to use these parameters to determine if fine soil samples classify as silt or clay. Sieve analysis was required to classify soils containing granular soil. With gradation and behavior qualities, the research team was able to assign USCS soil classifications to each sample. Another property determined from lab testing was the moisture content of each site sample. This value allowed researchers to determine how much groundwater affected the site.

3.4 LEM MODELING

Researchers conducted slope stability modeling using the Rocscience program SLIDE. Slope models were populated with soil strength properties. Executing LEM models with *in situ* strength properties, slope geometry, unit weight (γ), and groundwater conditions allowed researchers to determine the baseline FS for each site.

The modeling program determines slope FS using the method of slices. By dividing the soil mass into individual, finite pieces, and applying static equilibrium conditions on each, the code determines forces driving failure and forces resisting failure. Combining the forces acting on each of the slices due to soil properties, geometry, and external factors, allows the program to determine the overall slope FS. The output from each model is a rendering of the slope and site conditions, the lowest computed FS, and the critical failure surface. An example is given in Figure 16, showing slices generated during computation. The default SLIDE failure mechanism used in this study is a circular surface.

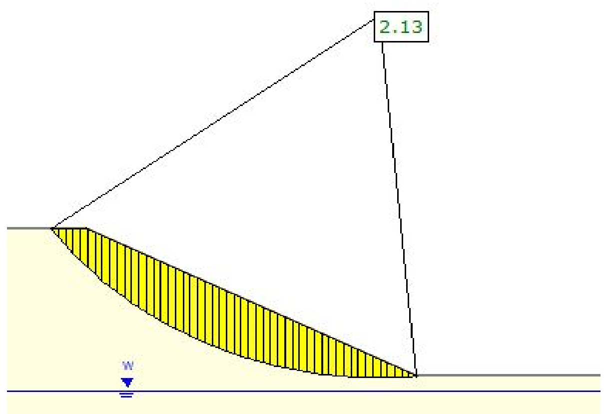


Figure 16: Example SLIDE slope stability model output

With the baseline FS for each site, researchers gauged the effect of each stabilization method. By comparing the baseline FS to the improved FS, researchers could quantify the effectiveness of the stabilization method. By modeling the same slope with a different stabilization technique, and using the same quantitative analysis, researchers determined the most effective stabilization method. Following this parametric study approach, researchers were able to develop a relative understanding of how much each technique improved slope stability. Analysis of all sites provided a case-by-case comparison. Researchers then made generalizations of the type ‘when *these* conditions are present, *this* appears to be the most effective stabilization option’ to develop the final deliverable.

3.5 INFINITE SLOPE ANALYSIS

The output from LEM modeling is the slope's FS against global rotational failure. Therefore, at sites with creep failure, the modeling output is not an accurate simulation of observed site characteristics. Infinite slope analysis uses a more simple calculation that considers slope inclination angle (β), soil effective friction angle (ϕ'), soil unit weight (γ), and unit weight of water (γ_w). Infinite slope FS for dry slopes is shown in Equation 2, and FS for saturated slopes is shown in Equation 3.

(Eqn. 2) $$FS = \frac{\tan(\varphi')}{\tan(\beta)}$$

(Eqn. 3) $$FS = \left(\frac{\gamma - \gamma_w}{\gamma}\right)\frac{\tan(\varphi')}{\tan(\beta)}$$

Infinite slope FS does not consider any benefit from cohesion. Since no samples were clean sand, all slope material observed had some cohesion; therefore, the FS from infinite slope analysis was conservative. Some SLIDE outputs showed failure surfaces with very large failure radii; this indicates that infinite slope analysis is a better way to asses FS.

3.6 SUMMARY

Site investigations and soil testing provided input data for slope modeling. Modeling sites with stabilization methods identified in the literature review allowed researchers to set up a parametric study. Identifying effective methods for each combination of site conditions led to recommendations summarized in the project deliverable.

CHAPTER 4: RESULTS, ANALYSIS AND DISCUSSION

Field investigations and laboratory tests provided soil parameters for each site. Authors developed LEM models for each site. Populating the models with strength values made a baseline model for each site. Authors developed models of each site with various stabilization methods applied, and noted the difference in output FS. Determining which stabilization methods were most effective for each combination of input conditions was vital in developing recommendations for the final deliverable. Slope geometry and supplemental information for each site can be found in Appendix B, and Appendix C shows the nearest DNR groundwater monitoring well to each site.

4.1 SITE VISITS

4.1.1 Carlton County Site

The Carlton County site was located on CSAH 6, approximately 7 miles east of Barnum, MN, near County Road 103. The location was described by the assistant county engineer, and the failure was identified by pavement distress. The site was covered with tall grass, as shown in Figure 17.

Figure 17: Carlton County site slope

In situ material was reddish brown lean clay with sand seams. The sand was brown to light brown and fine to medium-grained. The material under the embankment was borrow fill. *In situ* testing indicated average S_u values of 1.25 to 1.5 tsf. Correlated N_{60} values were approximately 2 blows per foot. No groundwater was encountered during sampling. Ojakangas (2009) and Hobbs and Goeble (1982) identified the region's geology as glacial drift. The observed fine-grained soil is consisted with glacial deposits. No slope stabilization attempts were observed.

4.1.2 Carver County Site

The Carver County site was located on County Road 40, on the Minnesota River north of Belle Plaine, MN. The location was recommended by the county highway department operations manager in the initial survey. Researchers noted some minor pavement distress. The guardrails along the road bend were pitched slightly from vertical, indicating soil creep, as shown in Figure 18. Site cover was primarily tall grass.

Figure 18: Carver County site slope, crooked guardrails indicate soil creep

Observed soil was brown to dark brown sand with silt. DCP testing indicated an increasing resistance to penetration with depth. Correlated N_{60} values ranged from 3 to 4 blows per foot. Pocket penetrometer test results on the *in situ* soil indicated S_u values between 0.5 and 0.75 tsf. The Minnesota River was approximately 50 feet from the toe of the slope. No standing water was observed, but the phreatic surface is relatively close to the toe of the slope, indicating possible drainage concerns. Geologically, the site was made up of river sediment from the Minnesota River (Ojakangas, 2009; Hobbs & Goebel, 1982), as indicated by the granular soil observed onsite. The investigation team did not observe any slope stabilization techniques in place.

4.1.3 Fillmore County Site

The Fillmore County site was located on CSAH 5, approximately 5 miles southwest of Chatfield, MN. The county engineer identified the location in the initial survey. The site was characterized by significant pavement distress, as illustrated in Figure 19. The Middle Branch Root River was near to toe of the slope. Investigators noted a large failure with clear scarp lines, characteristic of rotational slide failure, leaving vertical faces 1.5 to 2 feet tall (Figure 20 and Figure 21). The site was covered by tall grass. Topsoil extended 6 to 12 inches below the surface.

Figure 19: Pavement distress at Fillmore County Site

The soil was brown, fine-grained silty sand. Researchers conducted field sampling and *in situ* testing in an area inside and outside the failure region. S_u values ranged from 1.25 to 1.75 tsf. DCP testing results indicated that the top several blows (20 to 30 cm) had a relatively low resistance to penetration, with deeper material having a higher resistance. The soil's correlated N_{60} values were approximately 4 to 5 blows per foot. The geology of the site was weathered material on bedrock (Ojakangas, 2009; Hobbs & Goebel, 1982), consistent with soil observed. With the toe of the slope near a stream, the researchers identified groundwater and drainage conditions as a concern for this slope. As with several other slopes studied, the side of the road near a stream is failing, illustrating the importance of drainage. The field investigators did not observe any slope stabilization methods in place.

Figure 20: Clear rotational failure visible behind researcher at Fillmore County site

Figure 21: Scarp face at edge of failure at Fillmore County site

4.1.4 Houston County Site

The Houston County site was located on County Road 19, near a bridge over Riceford Creek approximately three miles northwest of Spring Grove, MN. The section of roadway was unpaved. Researchers met with a county engineering technician in Caledonia, MN to discuss the project history and details before visiting the site. The uphill side of the road exhibited no slope failure that affected the roadway. The downhill side of the slope was the subject of the repair and stabilization, shown in Figure 22. The slope's toe immediately bordered the creek. The technician indicated that a majority of the county's slope stability problems were due to large flooding events. The site slope failed after flooding in 2013.

Coarse rip rap covered the entire face of the slope. This is a common repair approach the county uses for slope failures. The plans specified a quarry-run rip rap, and grass seeding to cover. The county typically does not conduct a geotechnical investigation prior to implementing stabilization methods because maintenance teams have demonstrated success with the "rip-rap cover" method.

Figure 22: Houston County site slope

Soil was sampled on the slope above the roadway, shown in Figure 23, which was original slope material. Soil sampled was brown to dark brown silty sand. DCP testing was not performed at this site. Ojakangas (2009) and Hobbs and Goebel (1982) identified the geology of the region as weathered material on bedrock. The slope was located near a stream, providing an indication of groundwater depth. The immediate proximity of the toe of the slope to a stream indicated that groundwater is a concern for this site.

Figure 23: CSAH 19 Houston County site with steep uphill and downhill embankments

4.1.5 Koochiching County Site

The Koochiching County site was located on County Road 8, approximately ten miles southeast of Littlefork, MN. The research team met with the highway department maintenance supervisor in Littlefork and viewed three sites in the region. The first site, north of Littlefork, was a roadway that exhibited gradual creep failure down the slope, with a stream near the toe of the slope. The second site was on the Littlefork River where a culvert failure caused significant erosion and a large slope failure of the river bank.

The research team performed a field investigation at the County Road 8 site, shown in Figure 24. Researchers were informed that, like several other slope failures in the region, slope stability issues were first noted 15 to 20 years earlier; the pavement was repaired, but no slope stabilization methods were considered. The slope featured multiple small failures. The site was characterized by visible creep failure patterns and evidence of pavement repair.

Figure 24: Koochiching County site with visible soil creep

Researchers performed testing and sample collection at two locations: inside and outside the visible failure zone. Soil encountered appeared to be brown to dark brown lean clay with some sand and trace gravel. Average S_u values were approximately 1 to 1.5 tsf. Correlated N_{60} values were approximately 5 blows per foot for tested soil. The Littlefork River was near the toe of the slope. Ojakangas (2009) and Hobbs and Goebel (1982) described the geology of the region as lakebed of Glacial Lake Agassiz. The cohesive material observed at the site is consistent with glacial lake sediment.

4.1.6 Lac qui Parle County Site

The Lac qui Parle County site was located on CSAH 20 between the Minnesota River and Lac qui Parle Village. The county engineer met the project team onsite to describe erosion issues in the area. There was minimal to no evidence of slope failure affecting the roadway, as shown in Figure 25, but there was some slope failure at the edge of the fields. The main concern was erosion of back slopes between planted fields and the ditch. The investigation team noted several examples of erosion from field runoff causing washout similar to rotational slope failure, as shown in Figure 26.

Figure 25: Steep backslopes along CSAH 20 in Lac Qui Parle County

Field testing and soil sampling was conducted near the erosion-induced slope failure. Soil encountered during testing was light brown to brown fine to medium-grained sand with trace gravel. The soil had correlated N_{60} values ranging from 5 to 7 blows per foot. Pocket penetrometer testing at the failure indicated S_u values of 1.25 to 2 tsf. Ojakangas (2009) and Hobbs and Goebel (1982) identified the geology of the region as sediment from the Minnesota River, consistent with observed soil onsite. The county engineer provided project documents from recent roadwork (grading in 2013 and surfacing in 2014). Ground cover did not seem to influence slope stability at the failure location. Landowner property boundaries and right-of-way concerns caused geometry limitations next to planted fields. Areas with naturally forested uphill cover did not show signs of failure. Water is the driving force of the failure.

Figure 26: Erosion at edge of planted field causes slope failure in Lac Qui Parle Co.

4.1.7 Marshall County Site

The Marshall County site was located on 280th St. NW, approximately 7 miles northwest of Warren, MN. The County Engineer identified the location in the initial survey. The site was characterized by multiple small failures down the slope. A drainage ditch with standing water was located near the toe of the slope. The site was covered by tall grass, making visible observation of the failure difficult from a distance. Topsoil extended 6 to 12 inches below the surface. The site is shown in Figure 27.

Figure 27: Marshall County site slope

Soil appeared to be gray to dark gray clay with trace sand. DCP testing indicated the soil's correlated N_{60} values were approximately 3 to 4 blows per foot. The geology of the site was sediment from Glacial Lake Agassiz (Ojakangas, 2009; Hobbs & Goebel, 1982); soil at the site was representative of glacial sediment. Given the toe of the slope was near standing water, the researchers identified groundwater and drainage conditions as a concern. As with other slopes studied, the embankment near a water source was failing, illustrating the importance of drainage. The presence of groundwater, frost susceptible soil, and cold weather made this site a good example of how the freeze-thaw cycle can affect slope stability and lead to creep failure. Researchers did not observe any slope stabilization methods.

4.1.8 Murray County Site

The Murray County site was located on CSAH 22 near Plum Creek, south of Walnut Grove, MN. Slope failure site was identified by evidence of pavement repair. The project team met the county engineer and highway department maintenance supervisor at the site. The slope had been repaired in 2014 using nearby fill, placed and compacted in lifts with geosynthetic reinforcement, as shown earlier in Figure 6. The reconstructed slope is shown in Figure 28.

Slope geometry data was provided by the county engineering department, and samples of both the recent fill material and original soil, taken from the undisturbed side of the road, were collected. The fill soil was light brown to brown lean clay with trace sand and the slope had grass cover. The original soil was darker brown lean clay. Correlated N_{60} value for the fill soil was approximately 2 blows per foot, and the native material from the opposite side had a correlated N_{60} value between 3 and 4 blows per foot. Ojakangas (2009) and Hobbs and Goebel (1982) described the geology of the region as the Altamont ground moraine. Moraines, which are deposits of glacial material, can include a variety of soil types. The nearby stream indicated groundwater concerns. Slope steepness, landowner and right-of-way considerations, and groundwater were issues on this site.

Figure 28: Murray County site slope after reconstruction with visible pavement repair

4.1.9 Olmsted County Site

The Olmsted County site, pictured in Figure 29, was located on CSAH 15 at County Road 117, west of Rochester, MN. The site was characterized by a steep backslope, leading up to a private yard. The slope exhibited clear failure marks, shown in Figure 30. The failure in the backslope did not appear to affect the roadway, or public right-of-way. The site was identified in the survey by the county maintenance engineer. The slope was covered by thick grass and brush, with some small trees at the top of the slope. Roots were evident in hand sampling, and topsoil extended to a depth of approximately one foot.

Figure 29: Olmsted County site slope

Observed soil was light brown silty sand. Sampling and *in situ* testing were conducted both inside and outside of the visible failure area. Results of DCP testing indicated roughly the top half of the DCP depth had low resistance to penetration, while the second half of the test depth exhibited more resistance. The failed soil had a correlated average N_{60} value of 2 blows per foot, and the soil that did not exhibit visible failure had an average N_{60} value of 3 blows per foot. Ojakangas (2009) and Hobbs and Goebel (1982) described the geology of the region as glacial drift.

Figure 30: Rotational failure scarp at Olmsted Co. site

No streams, bodies of water, or other local indicators of water table height were observed. No stabilization attempts were noted at this site.

4.1.10 Pennington County Site

The Pennington County site was located on MN-32, approximately 1 mile south of Thief River Falls, MN. The site was identified by the county engineer in the initial survey. The site was characterized by significant rotational failure, as illustrated in Figure 31. The Red Lake River was near the site and standing water was observed at the toe of the slope. The failure was characterized by clear scarp lines leaving vertical faces 3 to 5 feet tall. The site was covered with tall grass.

Figure 31: Pennington County site slope, clear rotational failure

The soil observed was light brown clay with some sand. *In situ* testing indicated S_u values of 0.25 to 0.75 tsf. DCP test results indicated N_{60} values of 3 to 4 blows per foot outside the failure zone. The DCP probe advanced under self-weight in the failed portion, indicating significantly low strength. Ojakangas (2009) identified the geology of the site as sediment from Glacial Lake Agassiz, consistent with the observed soil type. The geologic background identification is consistent with Hobbs & Goebel (1982). With the toe of the slope near standing water, groundwater and drainage conditions are of concern. Authors did not note any slope stabilization methods.

4.1.11 Redwood County Site

The Redwood County site was located on CSAH 11 south of the Minnesota River near Franklin, MN. The failure was identified by evidence of pavement repair. The county engineer noted the site location in the initial survey. The failed side of the road was covered with coarse aggregate and rip rap, as shown in Figure 32. The opposite, although apparently steeper, did not show signs of failure or stabilization attempts, as pictured in Figure 33. Site surface cover was thick grass, geosynthetic fabric, and rip rap. *In situ* testing and sample collection were conducted at the steeper, southern site.

Figure 32: Failed (east) side of Redwood County site slope and nearby stream

Soil observed was dark brown fat clay. Some sand seams were noted during sampling. Average undrained shear strength values were 0.5 tsf. DCP test results indicated poor penetration resistance in the top 1 to 1.5 feet, then a notably higher resistance deeper. The average N_{60} values for the site ranged from 4 to 5 blows per foot. Geologically, the site was composed of sediment from the Minnesota River and glacial till (Ojkangas, 2009). River sediment likely caused the sand seams. No standing water was observed in the ditch; however, a stream was present near the toe of the slope. Groundwater drainage conditions are likely a stability concern. Rip rap cover was evidence of slope stabilization attempts. Older rip rap indicates the site has been repeatedly repaired.

Figure 33: Opposite (west) slope, no observed failure at Redwood Co. site

4.1.12 St. Louis County and West Duluth Sites

The site representing St. Louis County, pictured in Figure 34, was located on County Road 535 near Greany, MN. The site was identified by a severe failure of the road embankment over a culvert and displacement of concrete roadway barriers over the failure. Slope damage was due to culvert failure and erosion causing the toe of the slope to fail. The county maintenance engineer, and regional maintenance superintendent met the project team onsite to discuss the project history. Site cover was grass, brush and small trees.

Figure 34: St. Louis County slope and displaced concrete barriers

Soil was gray to light brown lean clay with trace sand. County representatives indicated that the St Louis County Bridge Office will be conducting a geotechnical investigation of the site. Ojakangas (2009) and Hobbs and Goebel (1982) identified the geology of this region as sediment from Glacial Lake Agassiz, as indicated by the clay material observed. Groundwater was observed in the culvert at the toe of the slope.

A MnDOT engineer and project adviser identified another slope failure in St. Louis County, located in West Duluth on Grand Avenue. The failure is shown in Figure 35. The slope was covered with grass and the top of the slope was wooded.

Figure 35: West Duluth site slope

4.1.13 Washington County Site

The Washington County site was located on CSAH 21, approximately one mile south of Afton, MN. The site was identified by the assistant county engineer in the initial survey. While some pavement repair was apparent at the site, the main site identification was wire mesh and rock anchors covering the slope. The slope was very steep, and large portions of exposed rock were visible from the road, as shown in Figure 36. The team was provided two geotechnical reports from the slope project. The main face of the slope was covered with wire mesh and rock bolts, as pictured in Figure 37. This site provides examples of using surface cover (i.e. wire mesh) and reinforcing structures (i.e. rock bolts) to stabilize slopes.

Figure 36: Washington County site slope

Areas on the side and top of the slope were covered with grass and thin brush, with some small trees. Given the data provided by the county engineering department, the project team did not conduct DCP testing at this site. Soil samples showed brown silty sand at the top and base of the slope. Ojakangas (2009) and Hobbs and Goebel (1982) describe the geology of the region as the St. Croix drift of the Superior Lobe. No groundwater was encountered during sampling.

Figure 37: Wire mesh and rock bolt cover at Washington Co. site

4.1.14 Field Investigations Summary

Researchers investigated and documented fourteen sites. Of the documented sites, researchers observed five with primarily sandy soil, eight with primarily fine-grained soil, and one rock site. Slope failure was visible at nine sites, while four sites were already stabilized. The damaging effects of groundwater were observed in most site failures and repairs, indicating that controlling water is a valuable stabilization method. One site bridged a stream with a culvert that appeared to fail and cause slope damage, and three sites showed slope stability issues in back slopes. Table 2 summarizes the site investigations conducted by the research team in Task 1. The nearest DNR observation well number for each site is provided in Appendix C.

Table 2: Field investigation site visits

Date	County Sites Investigated
Nov. 10, 2015	St. Louis
Nov. 12-13, 2015	Carver, Redwood, Murray, Lac qui Parle
Nov. 19, 2015	Carlton
Nov. 23-24, 2015	Washington, Houston, Fillmore, Olmsted, West Duluth
Dec. 3, 2015	Koochiching
Aug. 8, 2016	Marshall, Pennington

4.2 SOIL CHARACTERIZATION AND STRENGTH PROPERTIES

4.2.1 Overview

Laboratory testing was performed during Task 3. Testing to determine *in situ* moisture content was conducted on samples collected during site visits, in general accordance with *ASTM D2216 – 10.*

Moisture content testing was completed shortly after samples were collected to avoid possible loss of moisture in storage. Researchers also performed laboratory testing to classify soil samples with USCS designation. Values of c' and ϕ' that were critical to modeling came from direct shear testing on samples collected during field investigations. Laboratory analysis provided a comprehensive background of materials at case study sites.

4.2.2 Classification

The researchers' final USCS classification for each soil sample is shown in

Table 3. Samples were collected with a hand auger, so sites are characterized by soils in the top several feet of the slope.

Table 3: Soil Classification for each site sample

Sample	**USCS Classification**
Carlton Co.	CL - Lean clay
Carver Co.	SP - Poorly-graded sand
Fillmore Co.	ML - Silt with sand
Houston Co.	SC - Clayey sand
Koochiching Co.	CL - Sandy lean clay
Lac Qui Parle Co.	SP-SM - Poorly-graded sand with silt
Marshall Co.	MH - Elastic silt
Murray Co. - Native	ML - Sandy silt

Murray Co. - Fill	SC - Clayey sand
Olmsted Co.	CL - Sandy lean clay
Pennington Co.	ML - Silt with sand
Redwood Co.	CH - Fat clay with sand

4.2.3 Laboratory Strength Testing

Direct shear testing provided strength properties for each sample. Results are provided in Table 4. Appendix D shows the individual test data outputs. Researchers limited the scope of analysis to slope failures that are common, recurring issues faced by county engineering teams. Due to extreme slope geometry and severe slope failure, the team excluded the sites in St. Louis and Washington Counties from lab and modeling analysis; a geotechnical engineering consultant, rock mechanics analysis, and a complete site assessment would be necessary at these sites. Additionally, researchers determined that some stabilization techniques, although commonly implemented in engineering practice, are not suited to simple, recurring slope maintenance. The methods with a more involved design process, such as soil nails, retaining walls and MSE wall design also require a specialty contractor, a geotechnical engineering consultant and detailed analysis. Soil strength parameters were used to develop models for analysis.

Table 4: Direct shear test results

Sample	**ϕ'**	**c'**
	(degrees)	(psf)
Carlton Co.	16	1220
Carver Co.	35	200
Fillmore Co.	35	150
Houston Co.	34	300

Koochiching Co.	24	400
Lac Qui Parle Co.	35	50
Marshall Co.	18	600
Murray Co. Fill	32	390
Murray Co. Native	22	900
Olmsted Co.	34	200
Pennington Co.	17	1275
Redwood Co.	21	750

4.3 SLOPE STABILITY MODELS

Researchers intended modeling results to cover a wide spectrum of scenarios, allowing analysis for the best option for a given slope. Not all models necessarily represented the most practical or common methods (such as replacing an entire slope with fill), but were investigated as part of parametric analysis. Numerical modeling involves approximating some values and experienced-based interpretation of results is ideal for LEM analysis. Modeling results were used to conduct a parametric study, not necessarily to describe an actual site's stability.

4.3.1 Validating Models

The goal of LEM modeling was to simulate stabilizing failed slopes. With *in situ* conditions of observed slope failure modeled, researchers expected the model output FS to be less than or equal to 1.0, confirming failure. LEM simulations of some failed slope situations (where FS should be less than 1.0) resulted in FS values greater than 1.0; this indicated that for some scenarios, especially creep failure sites, LEM modeling can over-estimate the FS. Researchers adjusted input values for failed slopes, lowering the FS to confirm an observed failure. One method was placing the water table at the slope surface, decreasing the FS significantly. Poor compaction, freeze-thaw cycling, or undocumented fill also lower *in situ* soil strength. Therefore, for sites with observed failures, researchers used decreased strength values until output FS values were less than 1.0, with a failure surface similar to conditions noted in the field. Figure 38 shows a failure validation example (from the Olmsted County site) with strength properties corresponding to poor compaction.

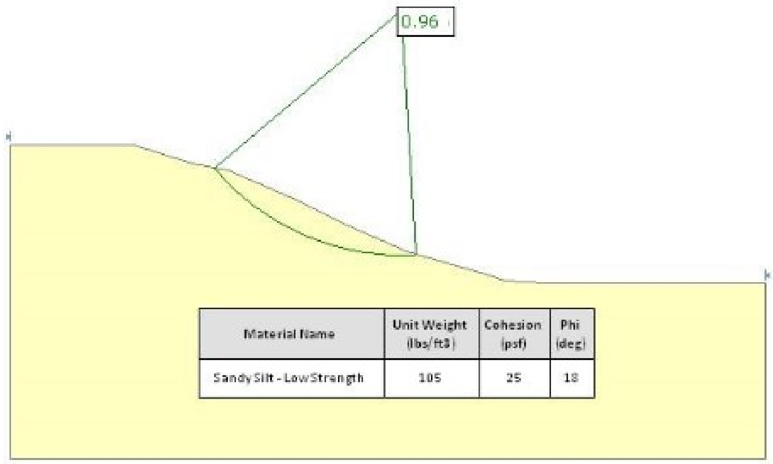


Figure 38: Example failure validation, output matches observed slope failure

The example in Figure 38 shows the geometry of a site where researchers observed a clear rotational slide. With a representation of *in situ* conditions, authors could note the effect of each method for the site.

4.3.2 Infinite Slope Analysis

Sites with observed creep failure were more difficult to validate, because the output from SLIDE identifies the circular plane with the lowest resistance to sliding. Therefore, sites that exhibit only creep failure have a higher output FS, even when modeling a situation where failure was observed. Model outputs of slopes with low values of c' exhibited shallow failure surfaces. As mentioned earlier, infinite slope analysis was performed, and can be used to represent sites exhibiting creep failure. Figure 39 shows the SLIDE output of a site with low cohesion; the capacity of this site to resist creep failure was best represented by infinite slope analysis, as indicated by the very large failure radius.

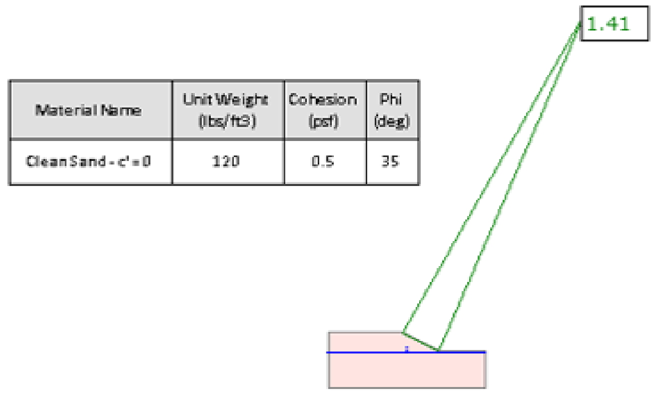


Figure 39: SLIDE output with low c', a site that is best represented by infinite slope analysis

Because LEM modeling can overestimate FS and infinite slope analysis does not consider c', the FS will be between the output from LEM analysis and infinite slope analysis for most sites. Since infinite slope FS values were calculated for each site, under dry and saturated conditions, the results can also be used to consider the effect of groundwater. Results of infinite slope analysis were considered where they were more applicable than LEM results. For these sites, the infinite slope FS was used as a baseline for recommending stabilization methods. The results of infinite slope analysis for appropriate sites are presented in Table 5. Authors considered both analysis types, but only used one for each site when determining the baseline for parametric analysis.

Table 5: Infinite slope analysis results for appropriate sites

Site	FS		Slope Angle	Soil Unit Weight	Soil Friction Angle
	Dry	Saturated	β (deg)	γ (pcf)	ϕ' (deg)
Carver	**2.16**	**1.08**	18	125	35
Fillmore	**2.16**	**0.93**	18	110	35
Houston	**1.32**	**0.69**	27	130	34
Koochiching	**3.17**	**1.59**	8	125	24
Lac Qui Parle*	**0.78***	**0.42***	42	135	35
Murray Fill	**1.23**	**0.61**	27	125	32
Olmsted	**1.85**	**0.96**	20	130	34

* Lac Qui Parle County failure due to erosion damage and surface washout.

4.3.3 Modeling Groundwater and Drainage Effects

Groundwater has a negative effect on soil strength. This is a fundamental concept in soil mechanics; as pore water pressure (u) increases, effective stress (σ') decreases. Because σ' governs soil strength, an increase in pore water pressure decreases soil strength. Researchers modeled the effects of groundwater by considering a steady-state, worst-case scenario. Assuming all drainage features failed, the groundwater table would rise, and the phreatic surface would be the same as the ground surface. An example from the Murray County site is shown in Figure 40.

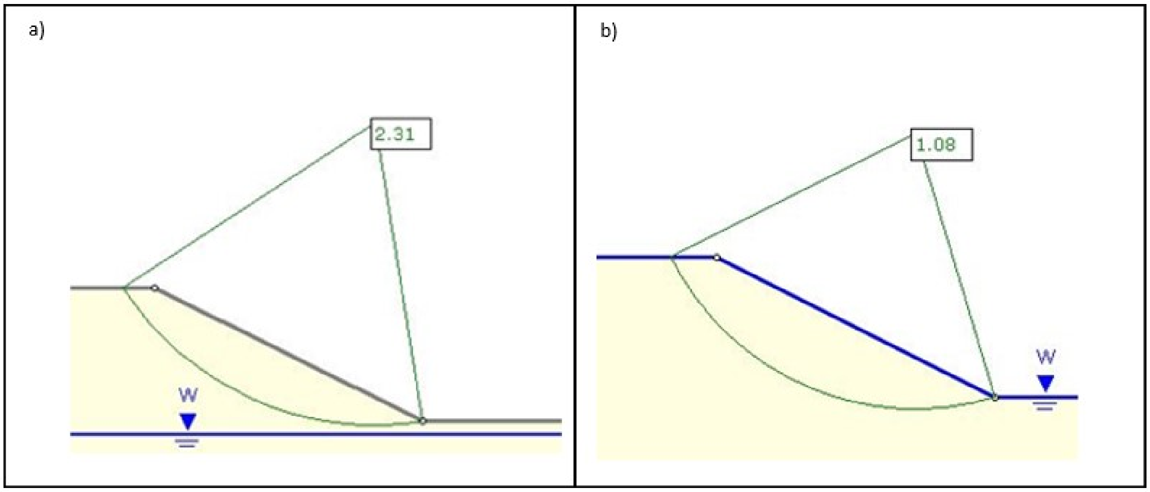


Figure 40: Groundwater effects, modeled by a) *in situ* and b) maximum, worst-case groundwater table heights

Installing drainage features returned the site to the hydrostatic conditions with a higher FS. Researchers did not consider transient groundwater analysis to represent a situation somewhere between the conditions shown in Figure 40. Any construction below the water table depth should involve detailed geotechnical analysis. These scenarios are outside the scope of the project.

Researchers considered both LEM models and infinite slope analysis in studying groundwater effects. For infinite slope analysis, noting the difference between dry FS and saturated FS quantified the effect of groundwater. Table 6 shows modeling results of sites with both *in situ* and worst-case groundwater conditions. Researchers noted that sites with higher ϕ' values were more sensitive to the presence of groundwater.

Table 6: Output results from modeling in situ and worst-case water table depths

Site	Analysis Method	FS		% change	ϕ' (deg)
		in situ Water Table	Worst Case Water Table		
Carlton Co.	LEM	9.63*	8.30*	13.8	16
Carver Co.	Infinite Slope	2.16	1.08	50.0	35
Fillmore Co.	Infinite Slope	2.16	0.93	56.9	35
Houston Co.	Infinite Slope	1.32	0.69	47.7	34
Koochiching Co.	Infinite Slope	3.17	1.59	49.8	24
Lac Qui Parle Co.	Infinite Slope	0.78	0.42	46.2	35
Marshall Co.	LEM	4.21*	3.76*	10.7	18
Murray Co. Fill	Infinite Slope	1.23	0.61	50.4	32
Murray Co. Native	LEM	2.21	1.57	29.1	22
Olmsted Co.	Infinite Slope	1.85	0.96	48.1	34

Pennington Co.	LEM	10.95*	8.95*	18.2	17
Redwood Co.	LEM	6.25~	4.32~	30.8	25

* Site did not fail, or model is of un-failed portion
~ Site had been repaired

4.3.4 Modeling Surface Cover

Surface failure was observed at several sites. Surficial soil creep can cause damage to pavement and roadways. Stabilizing the uppermost soil layer minimizes the effect of soil creep and limits pavement damage. For modeling, the research team considered a scenario with the top foot of *in situ* soil replaced with fill material, as shown in Figure 41. Covering a slope with coarse material does not typically require excavation. Researchers executed models with properties for course gravel and cobble rip rap. Material properties were considered with non-zero cohesion. Representative strength properties for common rock rip rap are (Attia et al., 2009): ϕ' = 45°, c' = 5 psf, γ = 120 pcf.

Surface cover does not typically increase the FS; in the case of rip rap cover, the method can increase weight and driving forces, which decreases the FS. Increasing strength properties of the cover material requires compaction, which can be difficult to achieve on the surface of a failing slope. Erosion protection is the main benefit, which is difficult to quantify and comes at the cost of increasing forces driving failure.

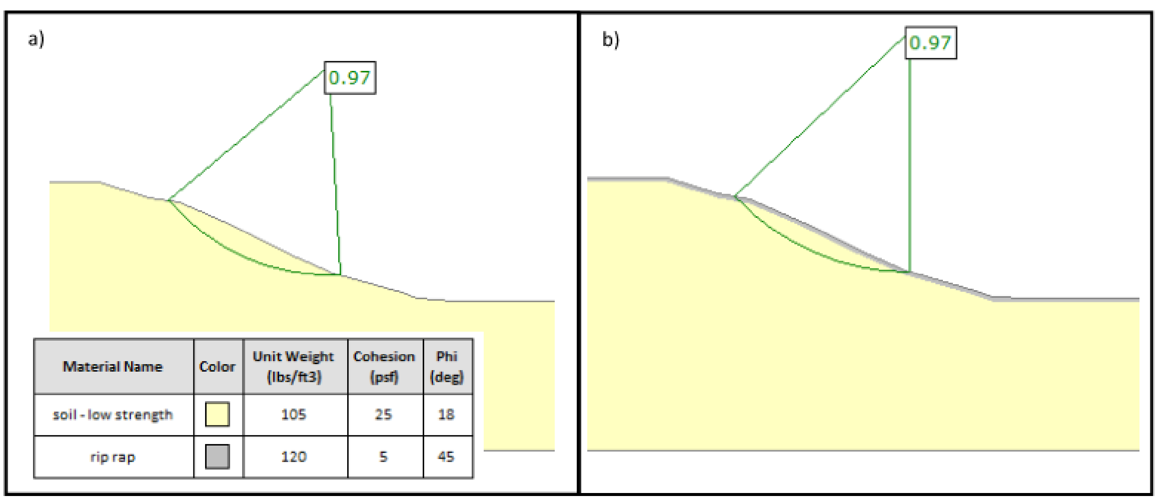


Figure 41: Example model a) with no surface cover, and b) with rip rap surface cover

Vegetative cover is another stabilization method. Operstein et al. (2000) concluded that soil with vegetation has higher shear strength and that plant roots affect strength by increasing overall effective cohesion. Observations from LEM modeling indicate that c’ governs the depth of the failure surface; a soil with higher c’ will have a deeper circular failure. Because plant roots have a quantifiable impact on c’, researchers recommend adding vegetative cover to slopes to increase surficial stability.

4.3.5 Modeling Buttressing

Another stabilization method is the construction of buttresses. The advantage of a buttress is that no excavation or slope reconstruction is required. Maintenance teams can simply place fill material against the toe of the slope. The same common borrow rip rap considered for surface cover can be used for buttress material, with the same material properties.

Researchers performed LEM tests on baseline slopes with buttresses extending various heights above the toe of the slope. An example from Lac Qui Parle County is shown in Figure 42.

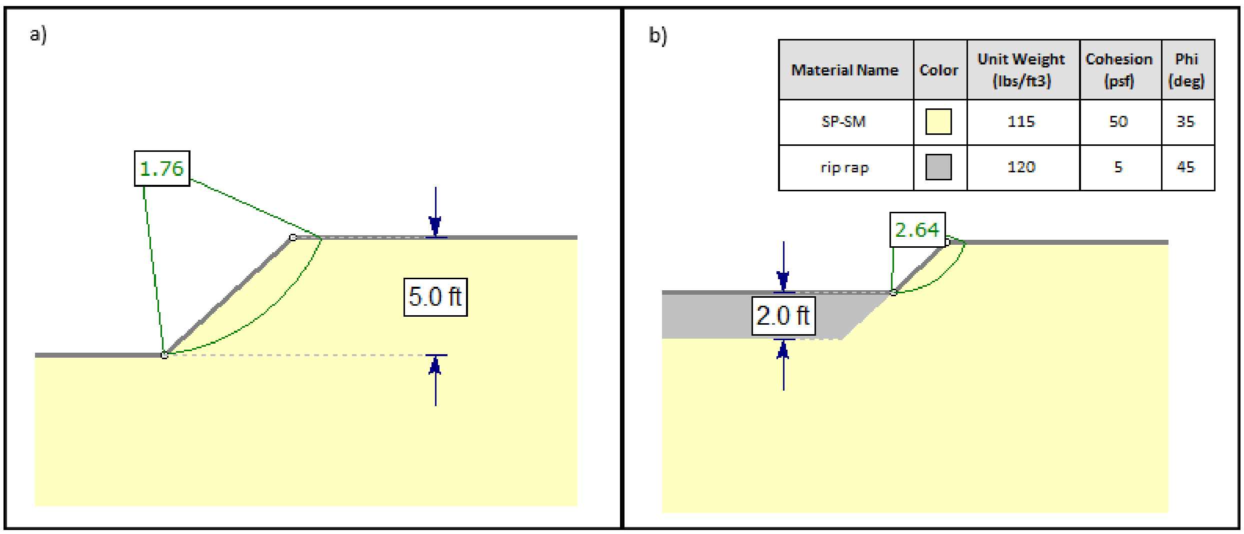


Figure 42: Example model a) without and b) with buttressing

As Figure 42 illustrates, an aggregate buttress affects the failure surface. The buttress material has higher strength properties, so the failure occurs in the soil. Researchers noted the most benefit in small slopes. Buttressing does not appear to be as effective as other methods for most slopes.

4.3.6 Modeling Regrading

Changing slope geometry, particularly decreasing slope angles, can reduce driving forces. If there is room in the right-of-way, shallow slopes (i.e. lower inclination angle) will be more stable. Regrading, even when not changing the overall slope angle, can increase the overall FS. The standard practice of re-compacting surface soil in benches, then finishing the slope to a specified grade generally adds stability. In some cases, geometric inconsistencies can cause local instability. Regrading is a way of 'smoothing out' irregularities. Shown in Figure 43, the overall FS at the Olmsted County site was noticeably improved by simply regrading the slope to the same overall angle.

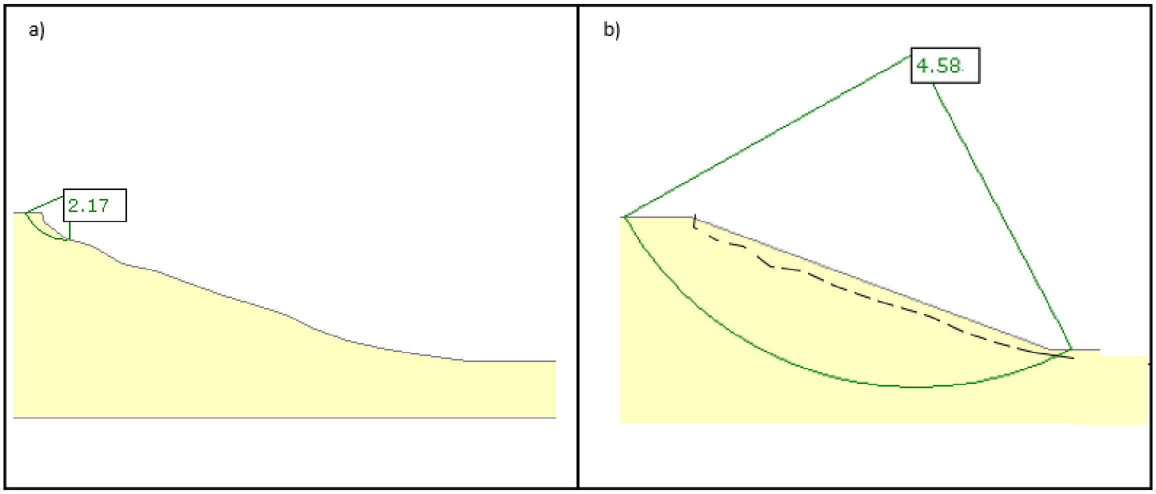


Figure 43: Model of regrading and 'filling in' geometric inconsistencies; a) original and b) regraded

While the Olmsted County site is not a typical example, regrading typically improves stability. For every method that required excavation, researchers assumed the benefit of regrading, proper construction, and re-compacting. Similar to new construction, for reconstruction and excavation stabilization projects, the slope is finished at a specified grade. This 'straight-line' slope face avoided geometric inconsistencies encountered *in situ* and, therefore, outputs exhibited a higher FS. Re-compaction also increases strength properties. When comparing 'before' and 'after' models of failed slopes, researchers were able to model the material with higher strength parameters after regrading and re-compacting.

4.3.7 Modeling Soil Replacement

Clean, free-draining sand is a material with ideal properties for roadway embankments. Replacing *in situ* material with a more suitable fill is a stabilization option, although typically more expensive than other methods. Authors conducted direct shear testing on coarse, compacted sand, and considered replacement material with the following properties: $\phi' = 35°$, $c' = 100$ psf, $\gamma = 120$ pcf.

The remove-and-replace method requires excavation, but likely not a specialty contractor. Researchers modeled three scenarios for soil replacement: replacing the top five feet of each slope with sand fill, replacing the top 10 feet, and replacing the entire slope. These extreme scenarios, although expensive, were considered to provide a relative understanding of the effectiveness of the method.

An important benefit of using sand fill to stabilize slopes is improving drainage properties. To model drainage, researchers considered worst-case drainage and adequate *in situ* drainage conditions for each site. The worst-case drainage scenarios were simulated by placing the water table immediately at the bottom of the fill layer, assuming the native material had poor or no drainage capability. The adequate *in situ* drainage situations were executed with the water table at its baseline depth. This can represent a native material with good drainage properties, or simulate drainage features installed in addition to sand fill. The example below shows the two drainage scenarios for replacing the top 10 feet of the same slope with sand. Figure 44 shows the worst-case drainage scenario and Figure 45 shows the model assuming adequate drainage for the same site.

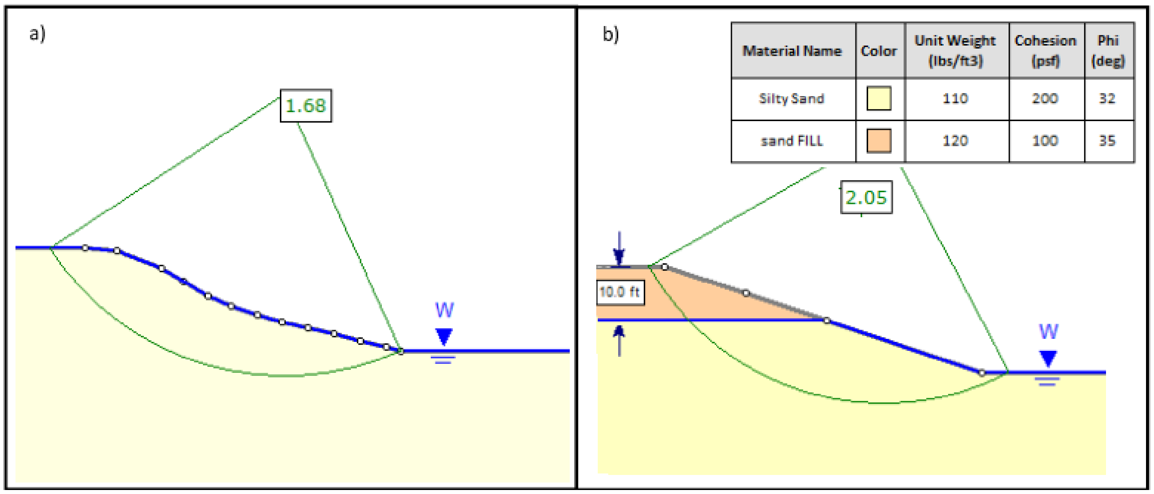


Figure 44: Example model of replacement with sand, worst-case drainage scenario; a) before and b) after replacement

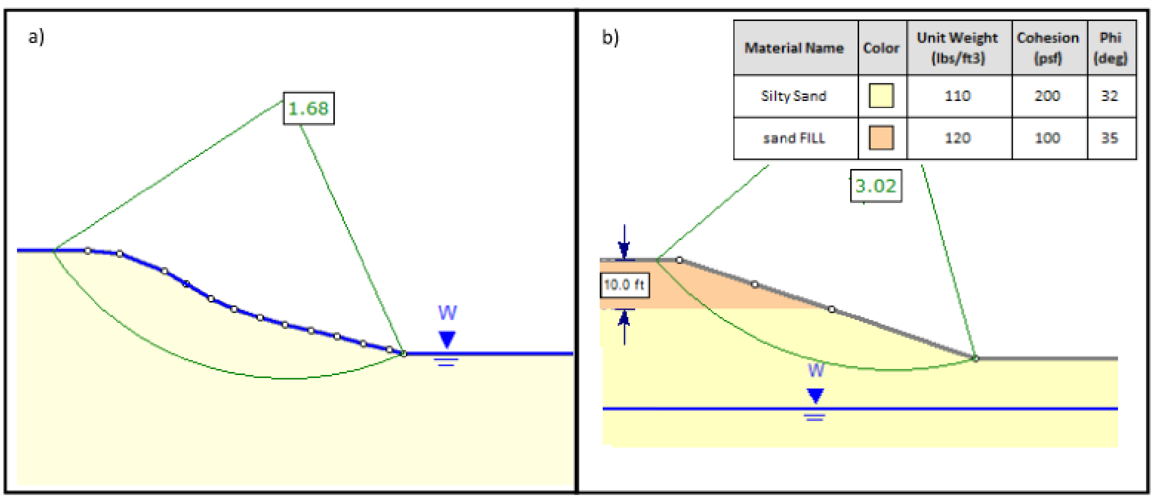


Figure 45: Example model of replacement with sand, adequate drainage scenario; a) before and b) after replacement and drainage feature installation

The worst-case scenario in Figure 44 simulated poor drainage in the slope and replacing the top portion of the slope with free-draining fill. The adequate drainage scenario shown in Figure 45 represents choosing to install drainage features; this will have a higher cost, but appears to be much more effective if *in situ* drainage is poor. Feasibility for the remove-and-replace method typically depends on availability of fill material. Sand fill should be covered after regrading to prevent erosion.

Another replacement fill option is expanded polystyrene (EPS) foam blocks, commonly called geofoam. The blocks can be easily placed in an excavation and dramatically decrease the weight of the slope. Researchers modeled the effects of EPS geofoam by treating the blocks as a new material layer. Direct shear testing on EPS geofoam (Padade and Mandal, 2014) led to the following strength properties: $\phi' = 6°$, $c' = 1250$ psf, $\gamma = 2$ pcf.

Researchers modeled scenarios which replace the entire slope depth with EPS geofoam to note the maximum difference in FS. An example of soil replacement with geofoam is shown in Figure 46.

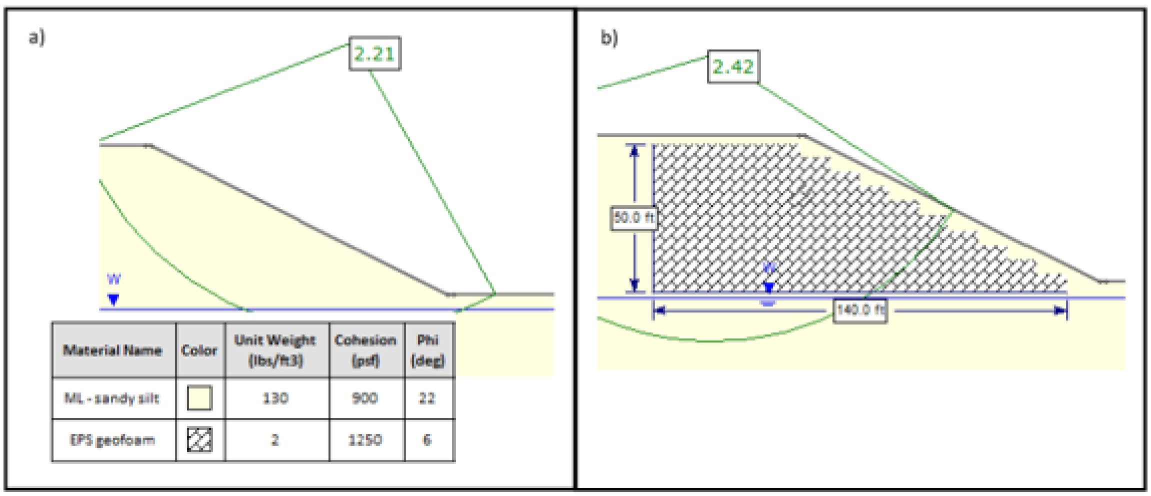


Figure 46: Example model simulating a) before and b) after implementing EPS geofoam

Researchers noted little to no benefit from using geofoam on most slopes. The greatest benefit was on the largest, heaviest slopes, where excavation would cost the most. This method requires extra consideration in areas with environmental sensitivity concerns. Due to material buoyancy, geofoam should not be used in flood planes. The use of EPS geofoam also requires excavation, and is likely a better consideration during the design of new slopes.

4.3.8 Geosynthetics and Other Stabilization Methods

Geosynthetic reinforcement can increase slope stability, and decrease the effect of erosion. Installing geogrid, geo-cells, or geoweb requires excavation. Researchers considered several scenarios involving geogrid, and found a wide variety of application methods and material properties. Strength properties vary for each manufacturer, and a geotechnical design process is necessary for each installation.

Therefore, geosynthetic reinforcement is outside the project scope. Geogrid is an option for increasing shear strength, but not a simple stabilization method for recurring slope maintenance.

The literature review identified several structural reinforcement methods that increase slope stability, including retaining walls, soil nailing, helical piles, and MSE walls. These techniques are effective when applied correctly. In some cases it is appropriate to consider such methods. These solutions, however, are outside the scope of research.

4.4 DEVELOPMENT OF DELIVERABLE

Researchers analyzed modeling results to develop recommendations for the project deliverable. The intent of modeling was to build a body of understanding of slope failure and mitigation techniques to suggest approaches for common slope failure situations. The guide shows common slope failure types and site conditions. Users find the set of conditions that most closely match the observed slope stabilization site, and the guide recommends stabilization approaches based on project results.

The guide was developed to include site characteristics that future users are most likely to encounter. The tool is set up to use distinctions in three site conditions to characterize any given slope project: failure type (i.e. soil creep or rotational failure), soil type (i.e. cohesive or granular soil), and drainage condition (i.e. presence or absence of groundwater indicator). These distinctions most clearly categorize the site conditions that researchers observed during site investigations. The tool provides examples of the type 'if you see *this*, consider …' and suggests stabilization approaches for each situation based on modeling conclusions. Researchers expect users to follow the guide like a flowchart to arrive at the combination of site conditions that most closely matches the observed slope.

4.4.1 Site Distinctions Based on Failure Type

The type of slope failure has the largest impact on which stabilization methods are appropriate. The distinction for slope failure type is surficial soil creep vs. rotational failure, as shown earlier in Figure 15. If a circular rotational failure has been observed, excavation and slope reconstruction will likely be necessary. Creep failure often indicates surficial damage.

4.4.2 Site Distinctions Based on Soil Type

The broadest distinction in soil type is cohesive vs. granular. Visual inspection may distinguish between the two types, but laboratory testing is sometimes required. Soil strength parameters, especially c', control the depth of the failure surface. Sand typically has higher values of ϕ' and lower values of c' making it less likely to exhibit deep rotational slides. Slopes made of cohesive material will have more drainage concerns and are usually more susceptible to seasonal frost heave. Slopes made of exposed sand typically have more potential for surface erosion.

4.4.3 Site Distinctions Based on Drainage Concerns

If a stream or standing water is noted, conditions indicate that the steady-state water table is near the toe. The combination of a high water table and undesirable drainage conditions caused many failures observed in site visits. In modeling, proper drainage was the most beneficial stabilization method. The effect of groundwater was modeled by assessing the FS with *in situ* water table conditions, and worst-case water table conditions, as shown in Figure 40. A site's drainage condition is described as poor if general conditions allow groundwater to decrease soil strength, contributing to failure. Typically cohesive soils have poor drainage properties. Results from modeling both *in situ* and worst-case groundwater conditions are shown in Table 6.

4.5 FINAL DELIVERABLE LAYOUT AND SCENARIO DESCRIPTIONS

Following the three categories previously mentioned will result in eight possible scenario descriptions. The end results of following the tool in development are shown in Table 7.

Table 7: Overview of scenarios outlining the final deliverable

Name	Failure Type	Soil Type	Groundwater Concerns?
Scenario #1	Rotational Slide	Cohesive	Yes
Scenario #2	Rotational Slide	Cohesive	No
Scenario #3	Rotational Slide	Granular	Yes
Scenario #4	Rotational Slide	Granular	No
Scenario #5	Surficial Creep	Cohesive	Yes
Scenario #6	Surficial Creep	Cohesive	No
Scenario #7	Surficial Creep	Granular	Yes
Scenario #8	Surficial Creep	Granular	No

4.5.1 Scenario #1, Rotational Failure, Cohesive Soil, Drainage Concerns

This is a common combination of site conditions. After a rotational failure, at least part of the slope will be rebuilt, so excavation is necessary. If the strength properties of the *in situ* material are not known, researchers recommend testing the soil. If soil has poor strength properties, regrading with engineered sand fill is the best option. After excavation, the new slope surface should be seeded to allow vegetative cover. Drainage features can be placed during repair and soil replacement. Drains and drainage wells can decrease the negative effect of groundwater. When groundwater concerns are present, researchers recommend installing drainage features. An example of Scenario #1 is shown in Figure 47.

Figure 47: Example of Scenario #1 from Pennington Co., MN

The Pennington County site is a clear example of Scenario #1. A small stream is located immediately at the toe of the slope, and a clear rotational failure surface is visible. To repair this slope, reconstruction and regrading will be necessary. For similar sites, maintenance teams should consider either remove-and-replace or regrading with *in situ* soil, adding drainage features, and vegetative cover.

A modeling example of the recommended remove-and-replace with drainage approach is shown in Figure 48. The model represents a rotational failure site with the suggested stabilization methods in place.

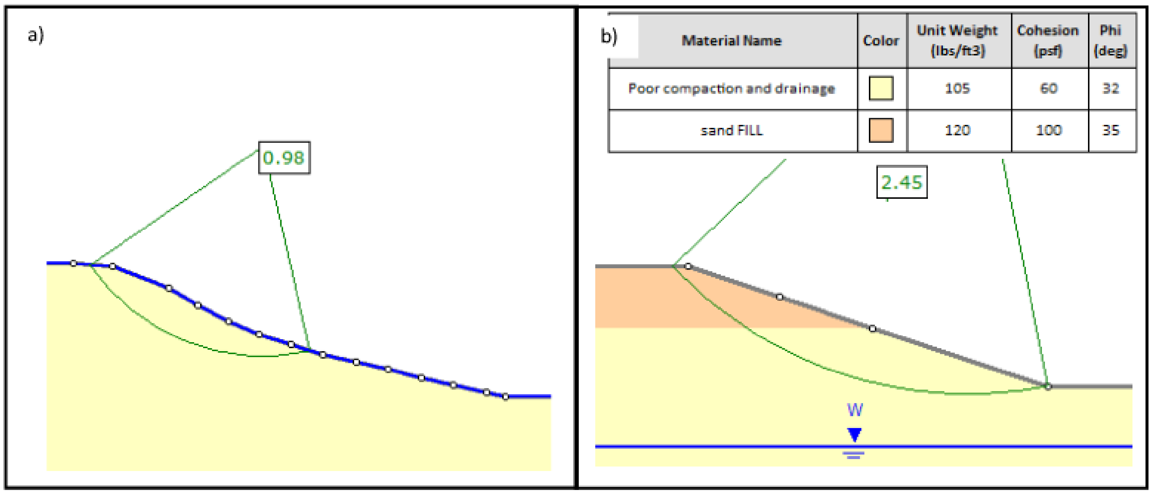


Figure 48: Model representing Scenario #1 a) with observed failure characteristics, and b) after implementing recommended stabilization methods

4.5.2 Scenario #2: rotational failure, cohesive soil, no groundwater concerns

The only difference from Scenario #1 is that the site has adequate drainage in this situation, and no nearby indication of a high groundwater table. A lack of obvious groundwater indicator like a stream or pond does not necessarily indicate lack of groundwater concerns. Installation of a standpipe or other inexpensive test for groundwater is recommended before distinguishing between Scenario #2 and Scenario #1. If groundwater is not a concern, the maintenance team can disregard considering drainage features. Reconstructing the slope is still necessary. Olmsted County is an example of Scenario #2 conditions; the observed failure is shown in Figure 49.

Figure 49: Example of Scenario #2 from Olmsted Co., MN

Many factors can cause soil to lose strength, such as poor compaction. Cohesive materials are more susceptible to frost heave than granular soils, so freeze-thaw fatigue may cause a loss in strength, leading to failure. For repair, maintenance teams should consider either remove-and-replace or regrading and compacting with *in situ* soil. Adequate cover, like local vegetation, is recommended. Figure 50 shows the SLIDE model researchers used to simulate the failure at Olmsted County and soil replacement repair.

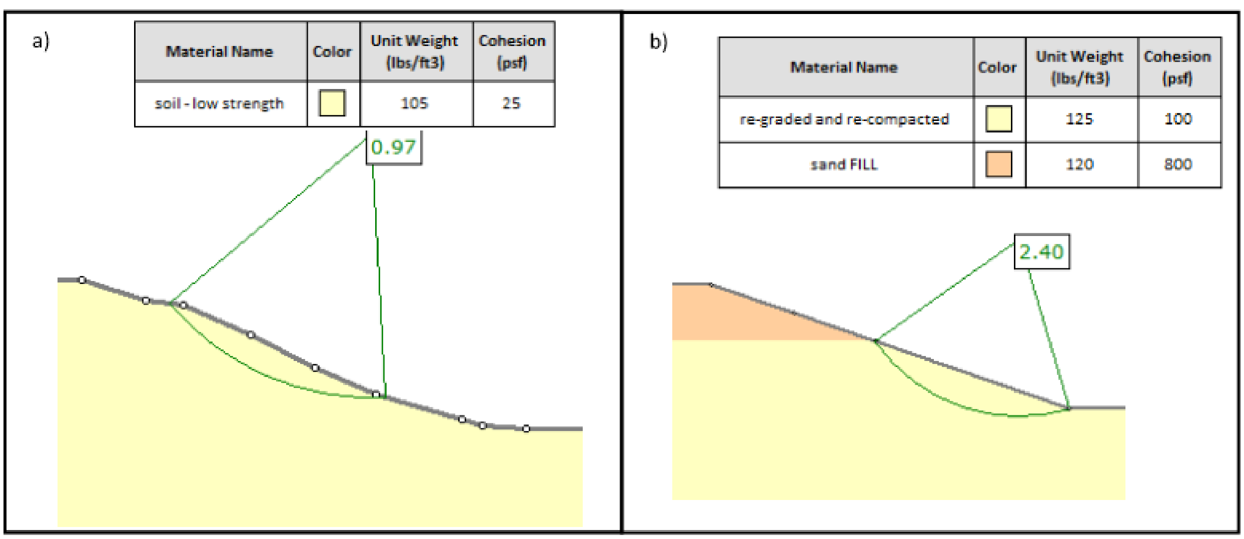


Figure 50: Model representing Scenario #2 a) with observed failure characteristics, and b) after implementing recommended stabilization methods

The demonstrated stabilization method is a partial soil replacement; the model shows a stability analysis of the slope regraded, with the top 10 feet replaced with sand fill. Replacing the failed material with fill of adequate strength properties improves the FS. Re-compacting material was simulated by the partial restoration of *in situ* strength properties. Regrading and re-compacting, when properly executed, increases soil ϕ' and c', leading to the increased FS.

4.5.3 Scenario #3: rotational failure, granular soil, groundwater concerns

The next major distinction is granular soil. Surface cover is very important for slopes with granular soil due to erosion. Surface erosion can cause geometric inconsistencies that impact slope FS, as shown earlier in Figure 43. Researchers did not observe any sites that match Scenario #3 in site investigations. As with other rotational failures, excavation and reconstruction is necessary. Because groundwater is a concern, drainage features are recommended to remove groundwater in the slope and lower the water table, increasing shearing resistance. Researchers recommend regrading, or if necessary, replacement with engineered fill. Maintenance teams should consider cover options that protect the slope from erosion, such as vegetative cover.

4.5.4 Scenario #4: rotational failure, granular soil, no groundwater concerns

Researchers noted sites with rotational failure due to groundwater. The distinction between Scenario #3 and #4 is the lack of groundwater concerns. Researchers observed one such site in Lac Qui Parle County, where field runoff caused damage at the surface, leading to global instability and a deep failure. This failure is shown in Figure 51. Although water was the driving force of the failure, groundwater did not affect the shear strength of the soil and cause the failure in the same way researchers described other rotational failures. The observed failure appeared to be a washout from surface water.

Figure 51: Example of Scenario #4 (from Lac Qui Parle Co. site)

The failure shown in Figure 51 is not a classical rotational failure. However, due to its depth and geometry, the stabilization and repair are the same as a traditional rotational failure. While this example does not appear to impact the roadway, reconstruction will be necessary for sites that do. As groundwater is not the primary reason for failure, the main source of loss of shear strength must be identified and mitigated. If erosion is the primary driving force, a more rigorous cover stabilization should be designed. Slope angle may also be a concern, as in the Lac Qui Parle Co. site. Right-of-way boundary issues caused the backslope to be constructed steeper than ideal, which created a larger force driving failure. If possible, decreasing the overall slope grade would increase stability. Researchers recommend regrading and compacting with *in situ* material. Extra consideration should be given to adequate ground cover to protect the slope from erosion damage.

4.5.5 Scenario #5: surficial creep, cohesive soil, groundwater concerns

Slopes exhibiting creep failure are sources of recurring slope maintenance. Surficial failure can cause pavement damage. A given site will be more likely to have drainage concerns if cohesive material is present. In this scenario, the groundwater causes creep failure. An example of this situation is shown in Figure 52.

Figure 52: Example of Scenario #5 (from Koochiching Co. site)

The observed failure at the Koochiching County site had a nearby indication of groundwater, and exhibited clear and persistent soil creep. The county representative mentioned that slopes exhibited new failures each spring. With groundwater present, and *in situ* material being frost-susceptible cohesive soil, frost heave is a likely cause of soil movement. Drainage features are the research team's main recommendation for slope stabilization. If creep is at the top of the slope, maintenance crews can also consider replacing the top portion of the slope with free-draining sand. This option would require excavation and the implied expenses. If the failure is near the bottom of the slope, a buttress can be an effective stabilization method, avoiding excavation costs.

4.5.6 Scenario #6: surficial creep, cohesive soil, no groundwater concerns

At sites where groundwater was not a concern, researchers noted soil creep more commonly than rotational failure. Surface creep, without the effect of groundwater, indicates failure near the top of the slope. Replacing the failed portion of the slope with an engineered fill is the recommended option for increasing sliding resistance. Researchers noted an example of Scenario #6, shown in Figure 53, where creep appeared at the top of a slope.

At the Murray County Site, it is clear how soil creep at the top of a slope can lead to pavement damage. In the absence of groundwater, poor compaction decreases the soil's shear strength. Replacing the poor soil with properly-compacted fill is recommended to stop soil creep.

Figure 53: Example of Scenario #6 (from Murray Co. site)

4.5.7 Scenario #7: surficial creep, granular soil, groundwater concerns

Adequate ground cover is essential to prevent erosion in slopes with sand. If adequate ground cover is present, the slope's failure behavior can be similar to Scenario #5. Researchers observed an example of Scenario #7 at the Carver County site, shown in Figure 54.

Figure 54: Example of Scenario #7 (from Carver Co. site)

The bent guardrail is evidence of soil creep. This particular example does not appear to be severely impacting the roadway. Proper drainage can remove groundwater from the area, increasing resistance to soil creep. Researchers recommend installing drainage features, and replacing failed soil with properly-compacted fill, or re-compacting *in situ* material.

4.5.8 Scenario #8: surficial creep, granular soil, no groundwater concerns

With no groundwater to lower soil strength, erosion is a concern. Surficial damage caused by erosion is not soil creep, but the movement type and stabilization attempts are similar.   Scenario #8 describes more of a surface washout; this failure type can undermine roadways and cause pavement damage. Researchers did not note any examples of Scenario #8 in field investigations. Ensuring adequate ground cover is important when observing surficial damage in slopes with granular fill. Damage at the top of the slope is best repaired by regrading. Maintenance teams can consider using a buttress at sites with damage in the lower part of the slope.

4.6 SLOPE STABILIZATION GUIDE FOR LOCAL GOVERNMENT ENGINEERS

Report authors expect end users to compare any given slope stabilization site to the scenarios provided in the guide layout. The guide contains a flowchart for users to determine which scenario to study. The scenarios were developed based on analysis of modeling results. Researchers' parametric study led to the recommendations in the deliverable. The guide is presented in Appendix E.

CHAPTER 5: SUMMARY AND CONCLUSIONS

This research project addresses needs for slope stabilization recommendations identified by local government engineers in Minnesota. Authors used input from the target audience, standard engineering research practices, and comparative analysis to help engineers with slope stabilization issues. The recommendations provided in the research deliverable will help improve the safety of roadway embankments, decrease the risk of slope failure, and limit preventable maintenance costs.

The project team followed a four-step approach to produce the slope stabilization recommendations guide. The intent was to focus on locally maintained slopes requiring recurring maintenance. In Task 1, the research team identified case histories representative of the project scope via a survey of Minnesota county engineering departments. Respondents identified stabilization methods and sites at which researchers could conduct field investigations. In Task 2, the authors researched various stabilization methods in a literature review. In Task 3, laboratory testing was conducted to characterize soil properties and provide strength parameters from site samples. LEM Models were developed and used to investigate the effect of various slope stabilization methods. A parametric study of each stabilization method and each site model led to stabilization recommendations. In Task 4, authors summarized the project's findings and presented recommendations in a slope stabilization guide for Minnesota county and local government engineers.

The guide was organized into eight scenarios because a major challenge in slope stabilization is the variety of problems and possible solutions. Often engineering experience, availability of material, and budget concerns govern repair method selection for county engineers. Authors expect the stabilization guide to assist local government engineers in effectively using budget and time resources. The deliverable was developed with resources typically not available to county engineering and maintenance departments, such as lab testing, advanced LEM modeling, and geotechnical analysis.

During analysis, authors developed some common recommendations. Controlling water is the most important stabilization method, and sensitivity to groundwater directly relates to the friction angle of the soil. Slope surfaces, especially in sand materials, should be covered to protect the embankment from erosion damage. The project deliverable aims to provide individual solutions for each problem users expect to encounter. The guide is presented in Appendix E. Future research could explore more detailed site investigations, consider stabilization methods involving geotechnical analysis or proprietary design, and use finite element analysis to explore transient groundwater conditions.

REFERENCES

1. Abramson, L. W., Lee, T. Sharma, S., Boyce, G. (2002). *Slope stability and stabilization methods* (2nd ed.). New York, NY: Wiley.

2. ASTM D2216-10. (2010). *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*. West Conshohocken, PA: ASTM International.

3. ASTM D2487-11. (2011). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*. West Conshohocken, PA: ASTM International.

4. ASTM D3080-11. (2011). *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*. West Conshohocken, PA: ASTM International.

5. ASTM D4318-10. (2010). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. West Conshohocken, PA: ASTM International.

6. ASTM D7380-15. (2015). *Standard Test Method for Soil Compaction Determination at Shallow Depths Using 5-lb (2.3 kg) Dynamic Cone Penetrometer*. West Conshohocken, PA: ASTM International.

7. Attia, M., Abdelrahman, M., Alam, T. (2009). *Investigation of Stripping in Minnesota Class 7 (RAP) and Full Depth Reclamation Base Materials.* Fargo, ND: Dept. of Civil Engineering, North Dakota State University.

8. Berg, R., Christopher, B., Samtani, N. (2009). *Design of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes – Volume II.* FHWA-NHI-10-025. Federal Highway Administration: Washington, DC.

9. Christopher, B., Gill, S., Giroud, J., Juran, I., Mitchell, J., Scholsser, F., Dunniclifff, J. (1990). *Reinforced Soil Structures – Volume I: Design and Construction Guidelines.* FHWA-RD-89-043. Federal Highway Administration: Washington, DC.

10. Coduto, D., Yeung, M., Kitch, W. (2011). *Geotechnical Engineering: Principles and Practices* (2nd ed.). Upper Saddle River, NJ. Pearson Education, Inc.

11. Collin, J., Hung, J., Lee, W., Munfakh, G. (2001). *Soil Slopes and Embankment Design Reference Manual*. Federal Highway Administration. FHWA NHI-01-026

12. Cornforth, D. (2005). *Landslides in practice: Investigations, Analysis, and Remedial/Preventative Options in Soils*. Hoboken, NJ: John Wiley and Sons.

13. Duncan, J. M., Wright, S. (2005). *Soil strength and slope stability*. Hoboken, NJ: John Wiley & Sons.

14. Gee, B. (2015). Geosynthetic materials help build optimized infrastructure. *Geostrata, 19*(2), 50.

15. Green, R., Olson, S., Cox, B., Rix, G., Rathje, E., Bachhuber, J., French, J., Lasley, S., Martin, N. (2011). Geotechnical Aspects of Failures at Port-au-Prince Seaport during the 12 January 2010 Haiti Earthquake. *Earthquake Spectra*. 27(S1).

16. Hobbs, H.C., Goebel J E. (1982). *Geologic Map of Minnesota, Quaternary Geology.* St. Paul, Minnesota: Minnesota Geological Survey.

17. Ojakangas, R. (2009). *Roadside Geology of Minnesota*. Missoula, MT: Mountain Press Publishing Company.

18. Operstein, V., Frydman, S. (2000). The influence of vegetation on soil strength. *Ground Improvement, 4*(2), 81-89.

19. Padade, A. H., Mandal, J. N. 2014. Interface strength behavior of expanded polystyrene (EPS) geofoam. *International Journal of Geotechnical Engineering.* 8 (1), 66-71.

20. Parametric Technology Corporation (PTC). (2010). Mathcad *Version 15.* Needham, MA: PTC.

21. Rahardjo, H., Hritzuk, K. J., Leong, E. C., Rezaur, R. B. (2003). Effectiveness of horizontal drains for slope stability. *Engineering Geology, 69*(3–4), 295-308.

22. Rocscience. (2016). SLIDE *Version 7*. Toronto, ON: Rocscience.

23. Stanic, B. (1984). *Influence of drainage trenches on slope stability*. 110(11), 1624-1636. Reston, VA: American Society of Civil Engineers.

24. Varnes, D.J. (1978). Slope Movement Types and Processes. *Special Report 176: Landslides: Analysis and Control.* Washington D.C: National Research Council.

25. Westfall, K. (2014). Geosynthetic reinforcement solutions for Lake Tahoe Highway. *Geosynthetics, 32*(1).

APPENDIX A: SLOPE STABILIZATION SURVEY

The research team sent this survey to each county engineering department in Minnesota. Respondents were asked about successful and unsuccessful stabilization attempts, and details about a slope stability site researchers could use for case studies in each department's jurisdiction.

Please select the number of locally-maintained slopes in your area of responsibility requiring recurring maintenance.

	0	1	3	4	5	6	8	9	10
Click or slide to correct choice									

Please provide the location of your worst slope or an example you would like the share with the research team in your area in the text box below.

Slope location

Please check each SUCCESSFUL method of slope stabilization that you have tried

- ☐ Natural (i.e., establish vegetation)
- ☐ Armor (i.e., rip-rap, concrete)
- ☐ Improve drainage (i.e. pipe culverts, wick drains)
- ☐ Replacement (i.e., replace original failed material with rock)
- ☐ Repair with original material (i.e., benching, recompacting, and drain tile)
- ☐ Other (please explain)

Please check each UNSUCCESSFUL method of slope stabilization that you have tried

- ☐ Doing nothing (i.e., allow failure and/or reconstruction)
- ☐ Natural (i.e., vegetation did not grow)
- ☐ Armor (i.e., rip-rap, concrete did not prevent slope failure)
- ☐ Repair with original material (i.e., benching and recompacting)
- ☐ Other (please explain)

Please indicate often you perform soils testing before attempting a slope stabilization method

- Never
- 0 to 20 % of slopes
- 20 to 40 % of slopes
- 40 to 60 % of slopes
- 60 to 80 % of slopes
- All of the Time

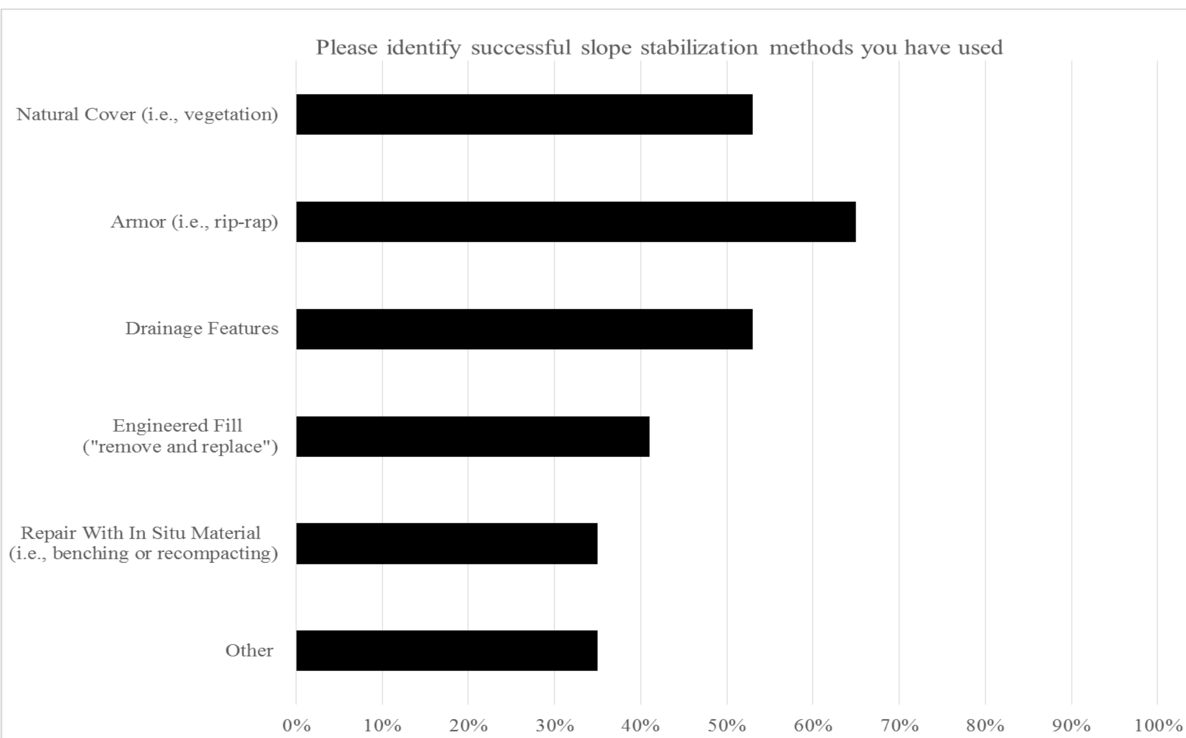
If available, please upload any site investigation data for your worst slope or an example you would like the share with the research team.

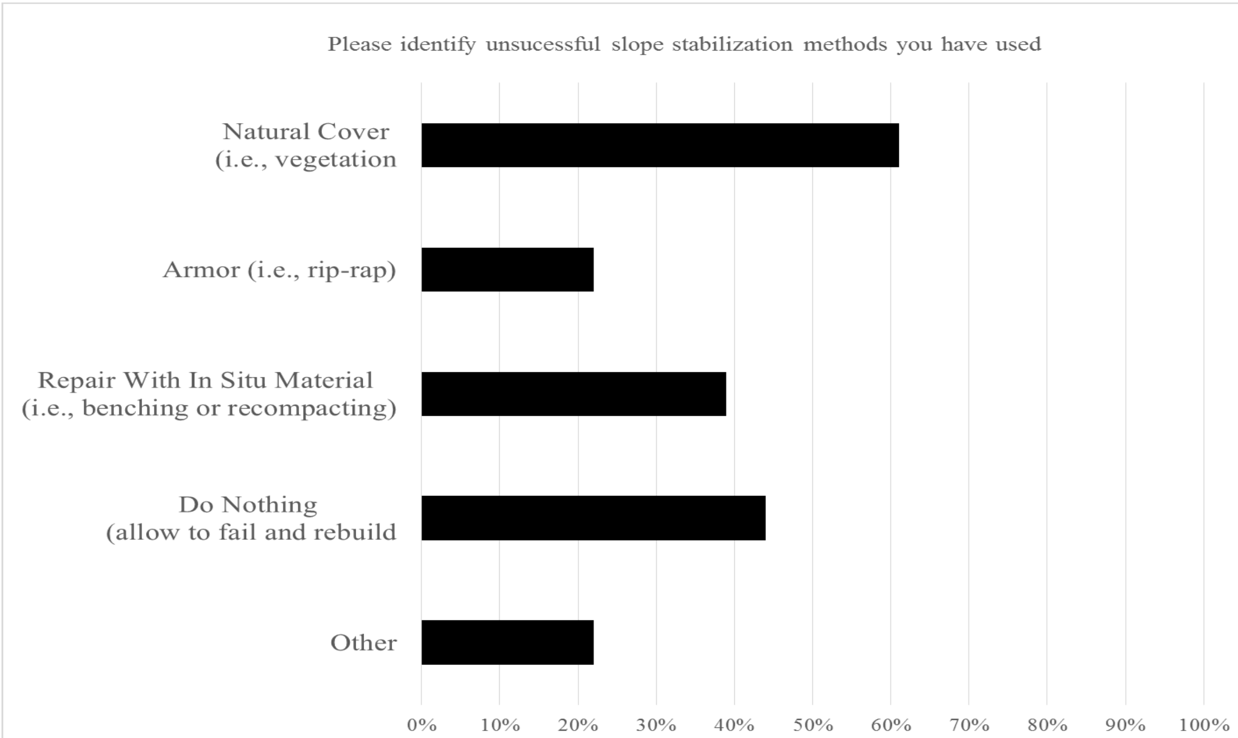
Choose File No file chosen

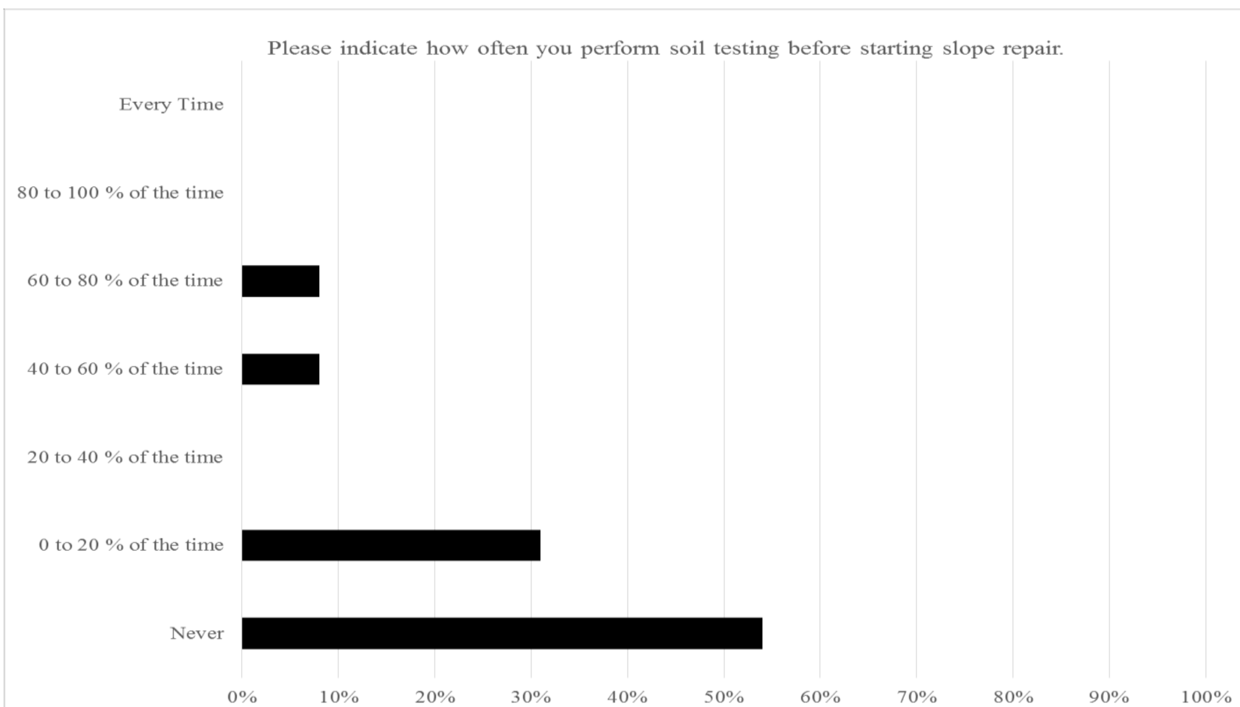
If available, please upload any soil testing data for your worst slope or an example you would like the share with the research team.

Choose File No file chosen

Please write in your full name, position, and jurisdiction.




Please identify unsucessful slope stabilization methods you have used
Natural Cover (i.e., vegetation
Armor (i.e., rip-rap)
Repair With In Situ Material (i.e., benching or recompacting)
Do Nothing (allow to fail and rebuild
Other
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%


Please indicate how often you perform soil testing before starting slope repair.
Every Time
80 to 100 % of the time
60 to 80 % of the time
40 to 60 % of the time
20 to 40 % of the time
0 to 20 % of the time
Never
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

APPENDIX B: SITE INVESTIGATION REPORTS AND SUPPLEMENTARY INFORMATION

This section provides a figure-dense summary of each site's location, geometry, topography, and other characteristics. Location within the state and county are identified for each site. Researchers used elevation data from the field to produce models in SLIDE. Supplemental information, such as soil properties and observed slope characteristics, are also provided.

Site Report: Carlton County

Field Investigation: 11-19-2015

Carlton County is located in the northeast part of the state. The site is located in the center of the county, east of Barnum, MN. Figure B1-1 shows the site location:

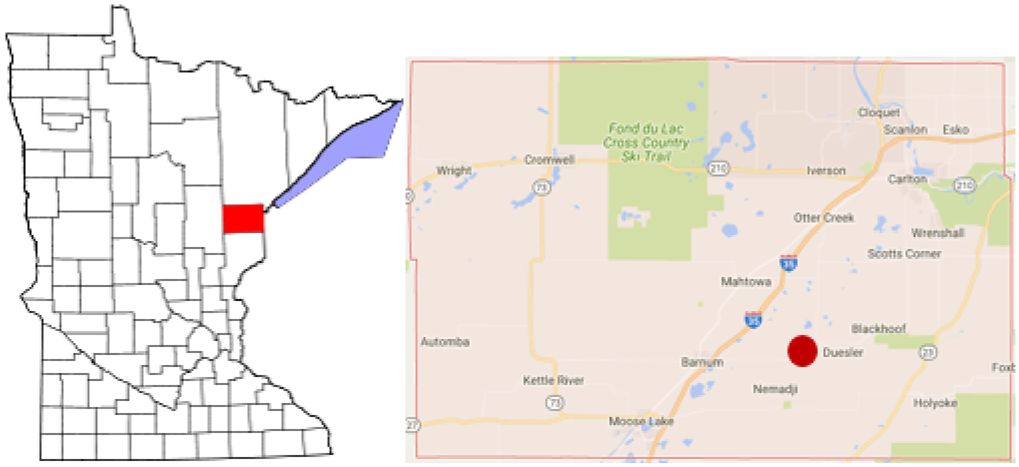


Figure B1-1: Carlton County site location

An aerial photo of the site is shown in Figure B1-2:

Figure B1-2: Carlton County site aerial photo

The site has the following approximate UTM coordinates: 15T N 5,152,500 E 539,800. Figure B1-3 shows the topography of the area, and approximate site location:

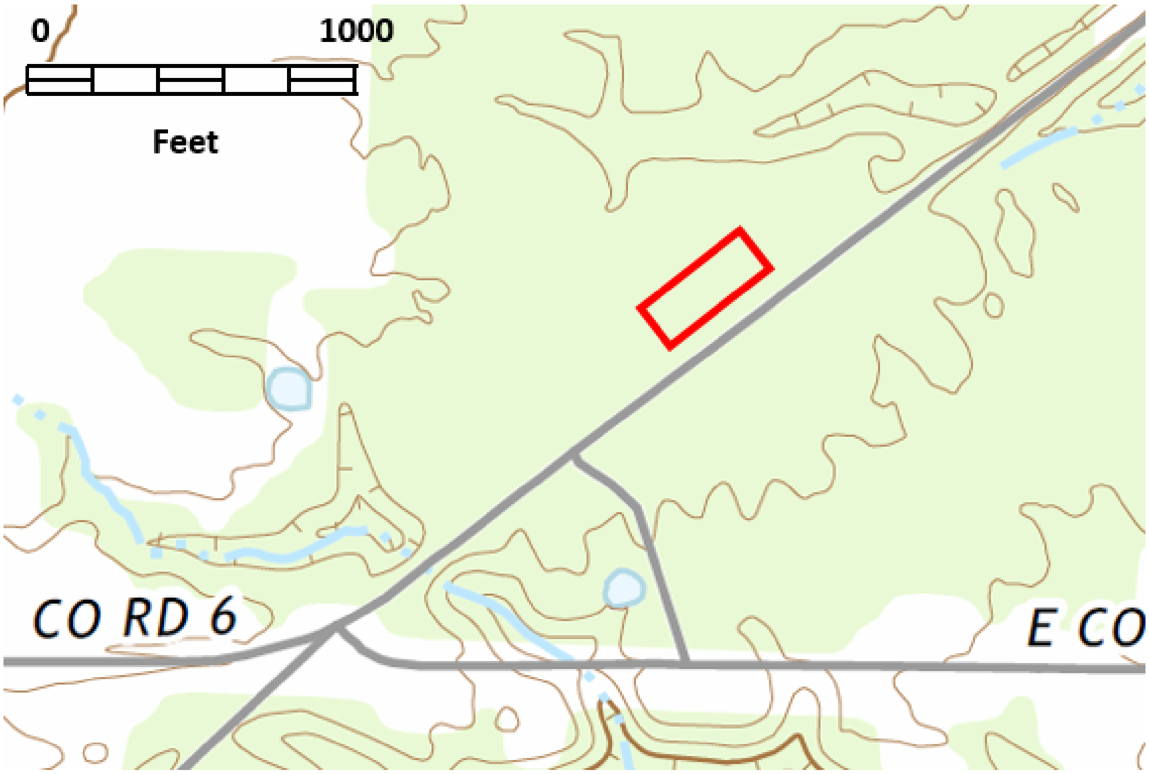


Figure B1-3: Carlton County site topography, from USGS Wrenshall Quadrangle, MN 7.5 Minute Map (2016)

The slope geometry was also determined, and a SLIDE model was produced. Figure B1-4 shows the model cross section.

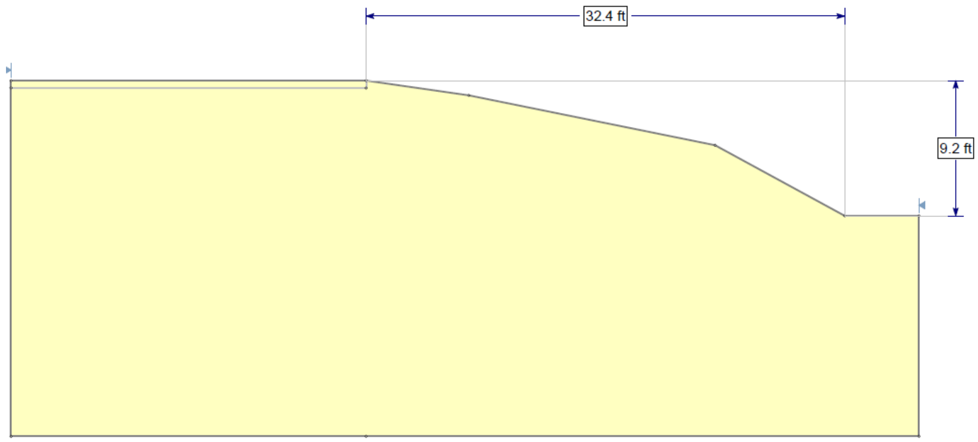


Figure B1-4: Carlton County site cross section

Investigators determined a number of soil properties from site visits, Table B1-1 summarizes these characteristics:

Table B1-1: Carlton County Soil Characteristics

Carlton County Site Soil Characteristics	
USCS Classification	CL - Lean clay
SPT Correlation, N_{60} (blows / ft)	2
Moisture Content, w (%)	31.1
Undrained Shear Strength, S_u (tsf)	1.25 to 1.5
Effective Cohesion, c' (psf)	16
Effective Friction Angle, ϕ' (deg)	1220

Investigators also made a number of observations about general site traits. These observations are summarized in Table B1-2.

Table B1-2: Carlton County Slope Characteristics

Carlton County Slope Characteristics Summary	
Slope failure observed?	No
Failure type	N/A

Evidence / indication of failure	N/A
Water present near toe?	No
Above / below roadway?	Below
Approximate steepness	3.5H : 1V
Observed Stabilization methods	N/A
Topsoil depth	0.5 to 1 ft

Site Report: Carver County

Field investigation: 11-12-2015

Carver County is located in the southwest part of the seven county Metro area. The site is located in the southern part of the county, approximately one mile north of Belle Plaine, MN. The location is shown in Figure B2-1:

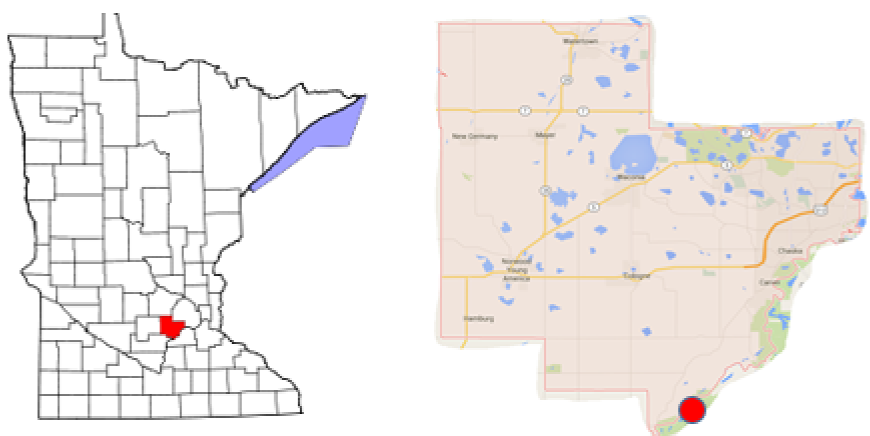


Figure B2-1: Carver County site location

Researchers conducted testing on the site at the noted location. The Minnesota River was present near the toe of the slope. Figure B2-2 shows an aerial photo of the site, investigation area, and surrounding features:

Figure B2-2: Carver County Site Aerial Photo

Site Topography is also shown in Figure B2-3. The UTM coordinates in Zone 15T are approximately N 4,943,700, E 439,900.

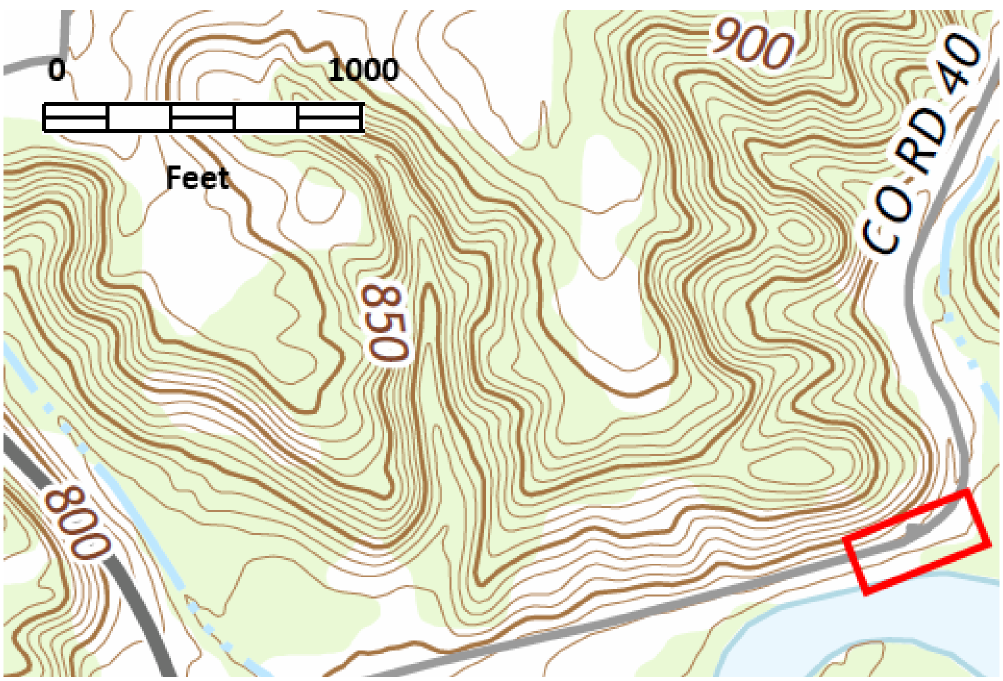


Figure B2-3: Topography for Carver County Site, from USGS Belle Plaine North Quadrangle, MN 7.5 Minute Map (2016)

The slope geometry was also determined, and a SLIDE model was produced. Figure B2-4 shows the model cross section. The slope has an overall steepness of approximately 3.5H:1V.

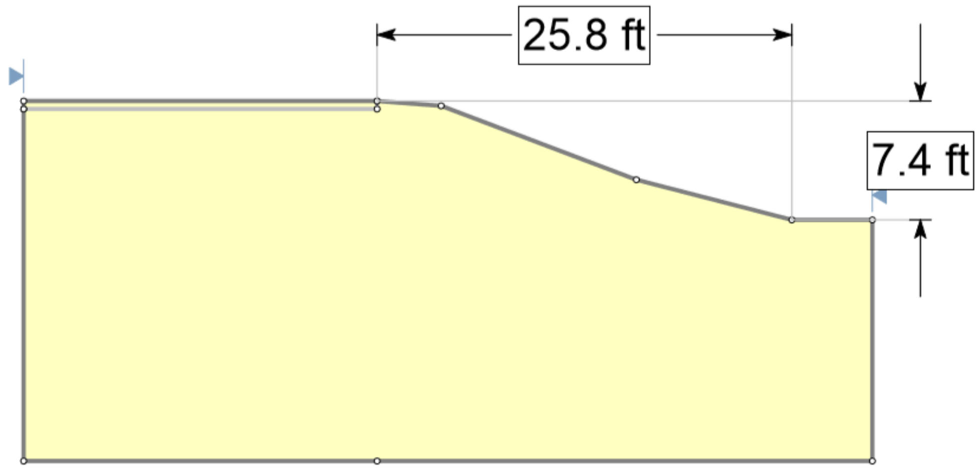


Figure B2-4: Carver County site cross section

Investigators determined a number of soil properties from site visits. Table B2-1 summarizes these characteristics:

Table B2-1: Carver County Soil Characteristics

Carver County Site Soil Characteristics	
USCS Classification	SP - Poorly-graded sand
SPT Correlation, N_{60} (blows / ft)	3 to 4
Moisture Content, w (%)	19.5
Undrained Shear Strength, S_u (tsf)	0.5 to 0.75
Effective Cohesion, c' (psf)	200
Effective Friction Angle, ϕ' (deg)	35

General slope observations and characterizations were also made, and are summarized in Table A2-2.

Table B2-2: Carver County slope characteristics

Carver County Site Slope Characteristics	
Slope failure observed?	Yes, no visible failure surface
Failure type	Creep
Evidence / indication of failure	Tilted guardrail posts
Water present near toe?	Yes - Minnesota River
Above / below roadway?	Below
Approximate steepness	3.5 H : 1V
Observed stabilization methods	N/A
Topsoil depth	0.5 to 1 ft

Site Report: Fillmore County

Field Investigation: 11-23-2015

Fillmore County is located in the Southeast part of the state, south of Rochester. The site is located in the northern part of the county, approximately five miles southwest of Chatfield, MN. The location is shown in Figure B3-1:

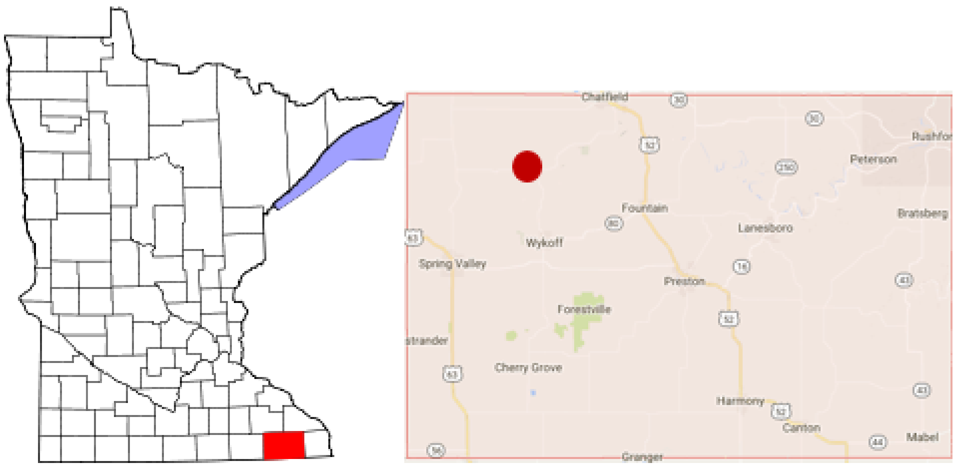


Figure B3-1: Fillmore County Site location

Investigators conducted field testing at the noted locations on the aerial photo, shown in Figure B3-2. The Middle Branch Root River was located near the toe of the slope.

Figure B3-2: Fillmore County site aerial photo

Site Topography and approximate location is also shown in Figure B3-3. The approximate UTM coordinates are 15T, N 4,849,700, E 561,700.

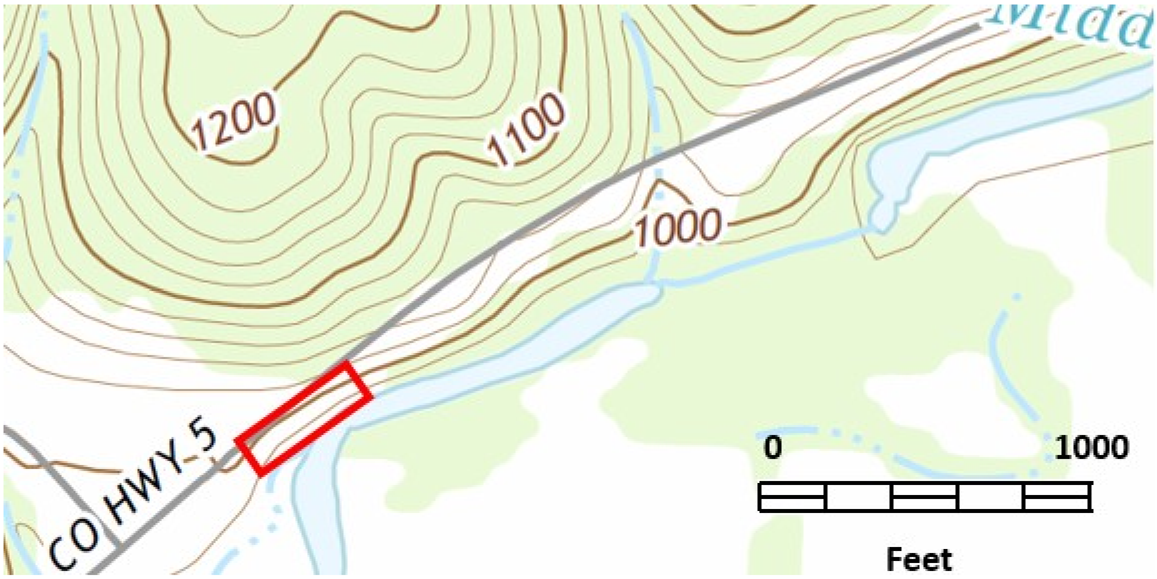


Figure B3-3: Fillmore County Site topography, from USGS Chatfield Quadrangle, MN 7.5 Minute Map (2016)

The slope geometry was also determined, and a SLIDE model was produced for use in Task 2. Figure B3-4 shows the model cross section, and Figure B3-5 shows the profile of the slope in the failed area. The slope has an overall steepness of approximately 3.5H:1V.

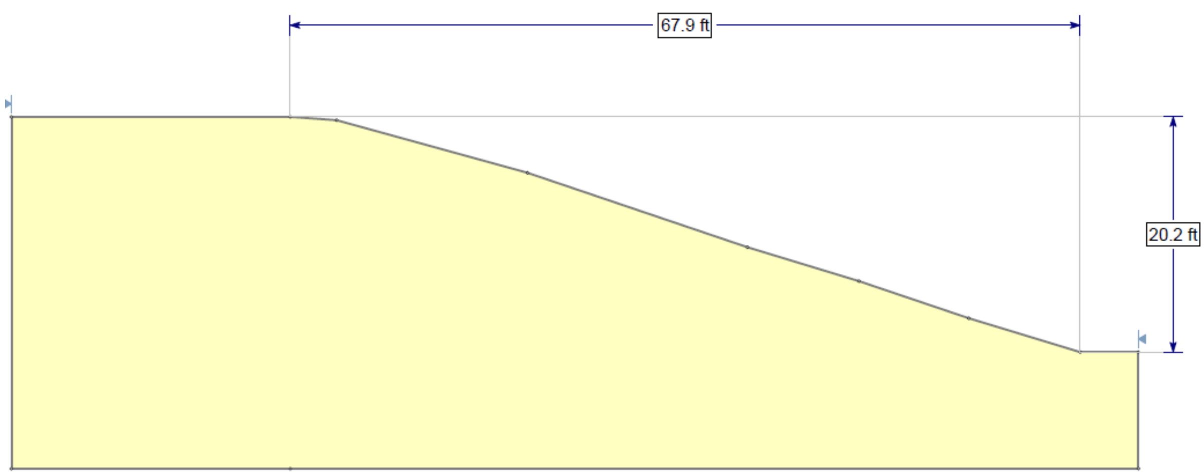


Figure B3-4: Original Fillmore County Site cross section

Figure B3-5: Fillmore County Site cross section, failed section

Observed site soil and slope characteristics are summarized in the following tables:

Table B3-1: Fillmore County Soil Characteristics

Fillmore County Site Soil Characteristics	
USCS Classification	ML – Silt with sand
SPT Correlation, N_{60} (blows / ft)	4 to 5
Moisture Content, w (%)	21.4
Undrained Shear Strength, S_u (tsf)	1.25 to 1.75
Effective Cohesion, c' (psf)	150
Effective Friction Angle, ϕ' (deg)	35

Table B3-2: Fillmore County Slope Characteristics

Fillmore County Slope Characteristics Summary	
Slope failure observed?	Yes
Failure type	Rotational
Evidence / indication of failure	Pavement failure, visible scarp

Water present near toe?	Yes- Middle Branch Root River
Above / below roadway?	Below
Approximate steepness	3.5H : 1V
Observed Stabilization methods	None
Topsoil depth	0.5 ft

Site Report: Houston County

Field Investigation: 11-23 2015

Houston County located in the southeast corner of the state. The site is located in the western part of the county, approximately three miles northwest of Spring Grove, MN. The location is shown in Figure B4-1:

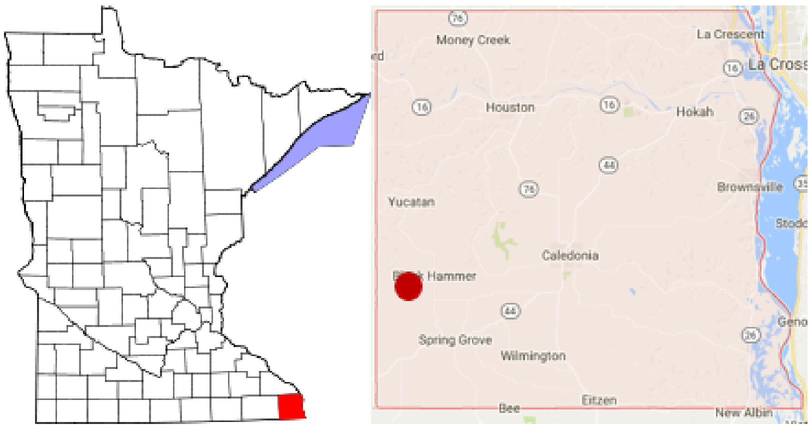


Figure B4-1: Houston County Site location

The Riceford Creek was present at the toe of the slope. Figure B4-2 shows an aerial photo of the site and surrounding features:

Figure B4-2: Houston County Site aerial photo

The site has approximate UTM coordinates 15T, N 4,629,000, E 604,000. Topography and approximate site location is shown in Figure B4-3:

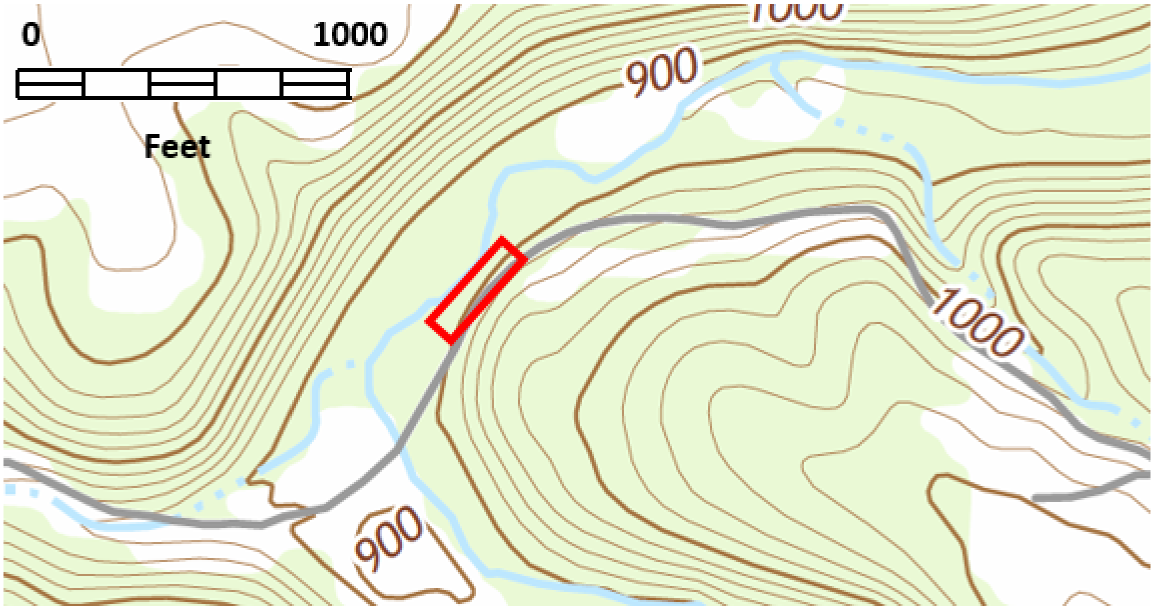


Figure B4-3: Houston County Site topography from USGS Spring Grove Quadrangle, MN 7.5 Minute Map (2016)

Site geometry was not measured. Plans were provided by the county highway maintenance technician; a typical cross section is shown in Figure B4-4:

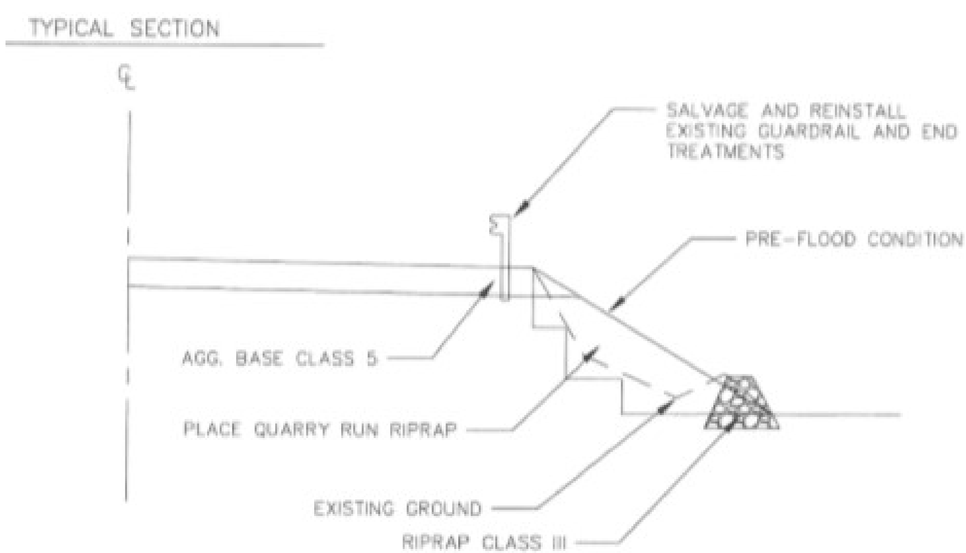


Figure B4-4: Houston County Site geometry (from Houston County Highway Dept.)

Soil and slope characteristics observed on site are summarized in the following tables:

Table B4-1: Houston County Soil Characteristics:

Houston County Site Soil Characteristics	
USCS Classification	SC – Clayey Sand
SPT Correlation, N_{60} (blows / ft)	Not tested
Moisture Content, w (%)	19.9
Undrained Shear Strength, S_u (tsf)	Not tested
Effective Cohesion, c' (psf)	300
Effective Friction Angle, ϕ' (deg)	34

Table B4-2: Houston County Slope Characteristics

Houston County Slope Characteristics Summary	
Slope failure observed?	No (repaired)
Failure type	Rotational
Evidence / indication of failure	Failure across road (repaired)
Water present near toe?	Yes - Riceford Creek
Above / below roadway?	Below
Approximate steepness	2H : 1V (repaired)
Observed Stabilization methods	Rip Rap cover
Topsoil depth	not measured

Site Report: Koochiching County

Field Investigation: 12-3-2015

Koochiching County is located on the border between Minnesota and Ontario, Canada, in the north – central part of the state. The site is located in the central part of the county, southeast of Littlefork, MN, as shown in Figure B5-1:

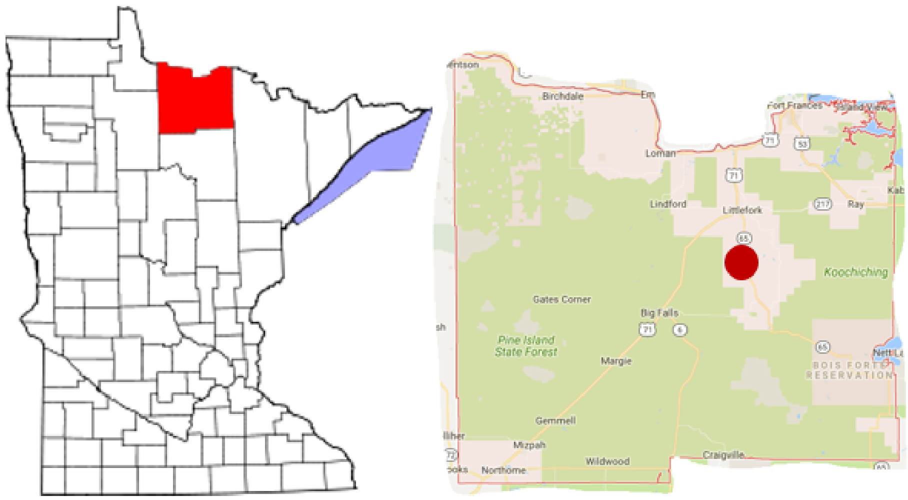


Figure B5-1: Koochiching County Site location

The Littlefork River is located near the toe of the slope. Figure B5-2: shows an aerial photo of the site, with the test locations and surrounding features:

Figure B5-2: Koochiching County Site aerial photo

Site Topography is also shown in Figure B5-3, along with approximate site location. The approximate UTM coordinates are 15T N 5,357,850 E 462,300.

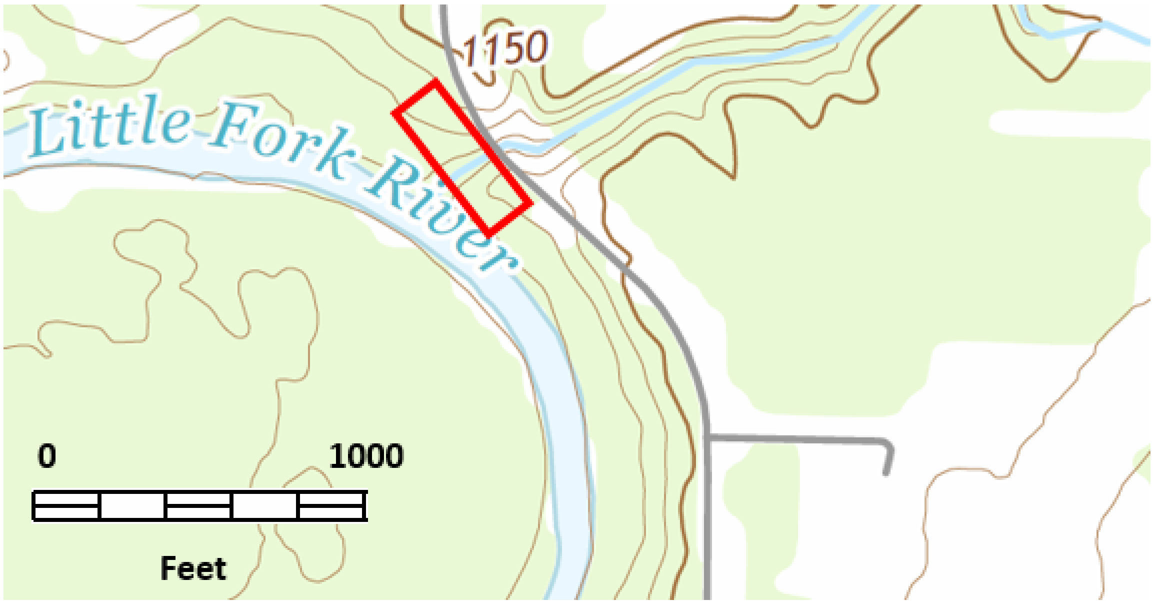


Figure B5-3: Koochiching County Site topography, from USGS Ericsburg SW Quadrangle, MN 7.5 Minute Map (2016)

The slope geometry was also determined, and a SLIDE model was produced. Figure B5-4 shows the model cross section. The slope has an overall steepness of approximately 6.5H:1V. Figure B5-5 shows a cross section in the failed area.

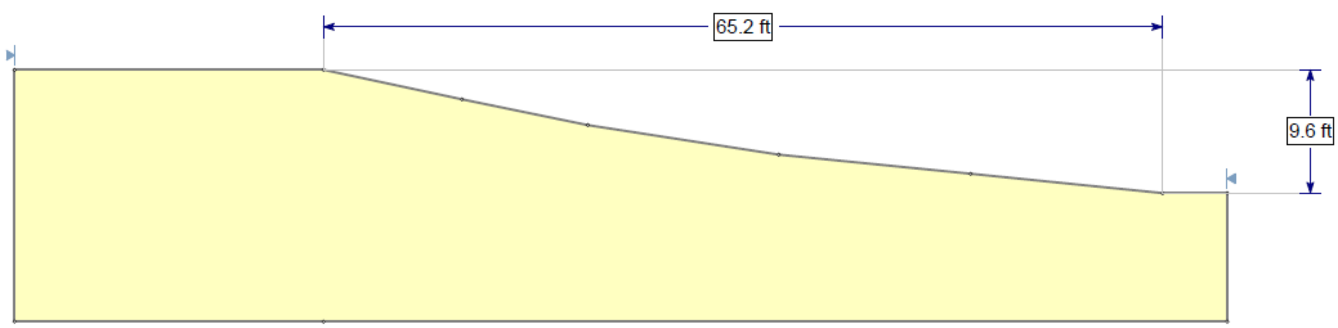


Figure B5-4: Koochiching County site cross section

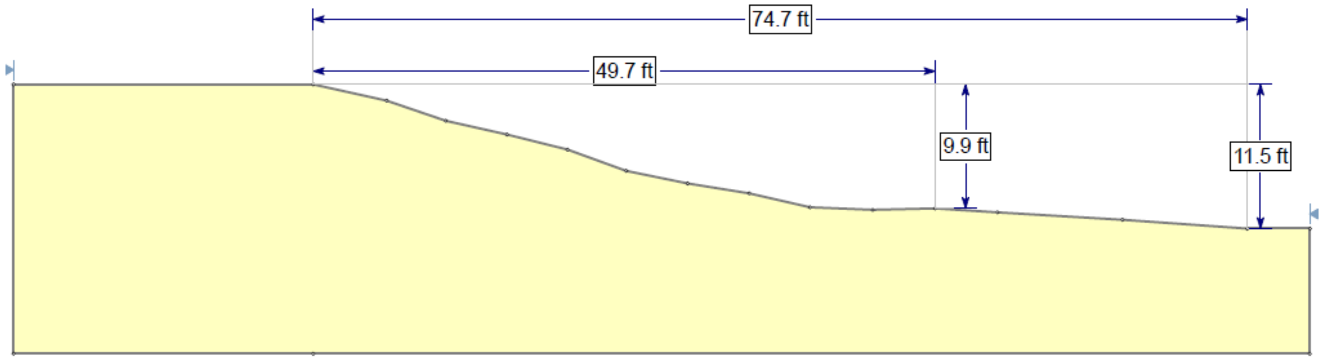


Figure B5-5: Koochiching County site cross section from failed zone

The following tables summarize soil and slope characteristics observed on site:

Table B5-1: Koochiching County Soil Characteristics

Koochiching County Site Soil Characteristics	
USCS Classification	CL - Sandy lean clay
SPT Correlation, N_{60} (blows / ft)	5
Moisture Content, w (%)	26.4
Undrained Shear Strength, S_u (tsf)	1 to 1.5
Effective Cohesion, c' (psf)	400
Effective Friction Angle, ϕ' (deg)	24

Table B5-2: Koochiching County Slope Characteristics

Koochiching County Slope Characteristics Summary	
Slope failure observed?	Yes
Failure type	Creep
Evidence / indication of failure	Visible Scarp on face
Water present near toe?	Yes - Littlefork River

Above / below roadway?	Below
Approximate steepness	6.5H : 1V
Observed Stabilization methods	None
Topsoil depth	0.5 to 1 ft

Site Report: Lac Qui Parle County

Field Investigation: 11-13-2015

Lac Qui Parle County is located in western Minnesota, and borders South Dakota. The site is located in the eastern part of the county, between Lac Qui Parle Village and the Minnesota River. The location is shown in Figure B6-1:

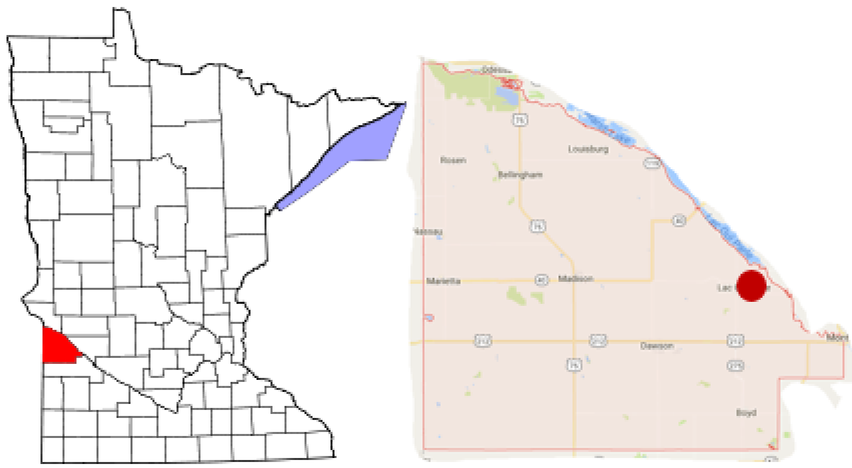


Figure B6-1: Lac Qui Parle County site location

There was not one single site of investigation. The concern was backslope failure along planted fields along County Road 20. Figure B6-2 shows the road and fields along which backslope failures were observed:

Figure B6-2: Lac Qui Parle County site aerial photo

The road has approximate UTM coordinates 15T N 4,986,100, E 272,000 to E 277,000. Figure B6-3 shows topography along the road:

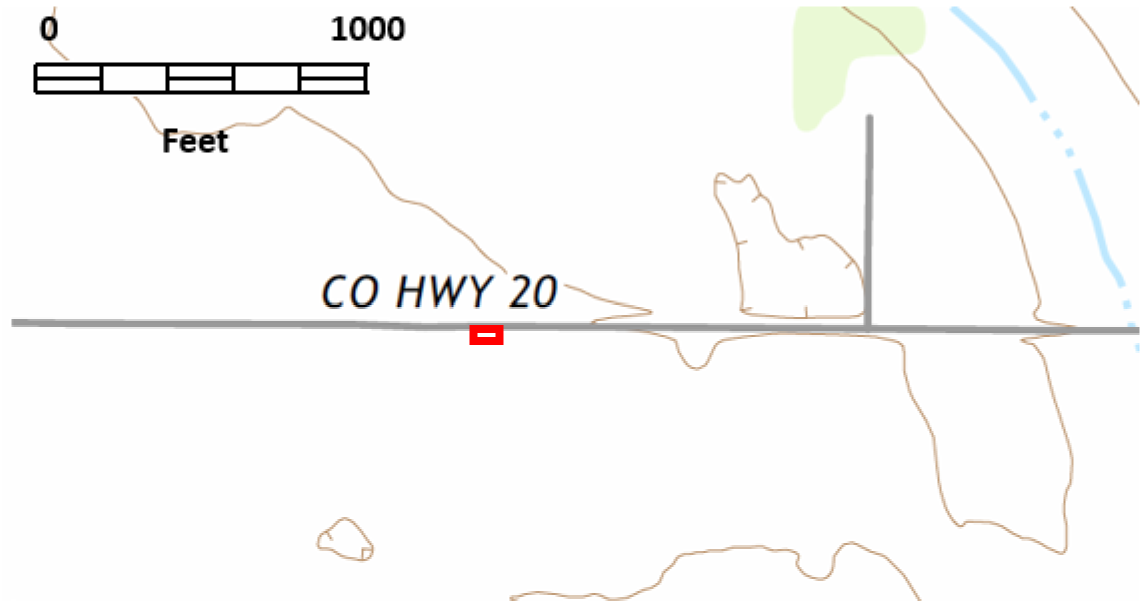


Figure B6-3: Lac Qui Parle County site topography, from USGS Clarkfield NE Quadrangle, MN 7.5 Minute Map (2016)

Steep backslopes appeared to be the main concern for this site investigation. A typical cross section is shown in Figure A6-4:

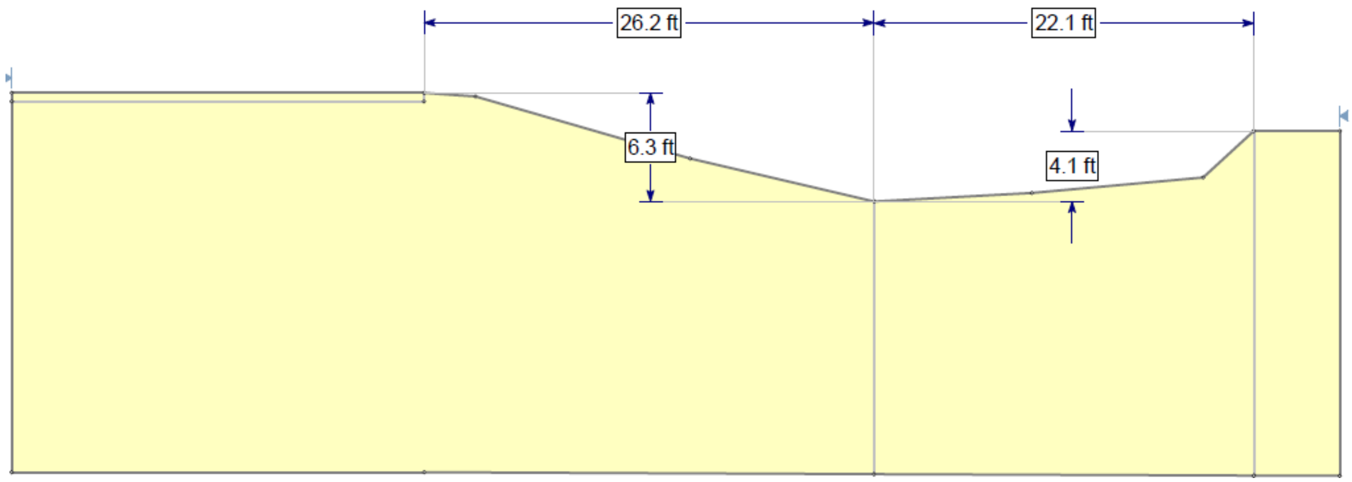


Figure B6-4: Lac Qui Parle County site cross section

The following tables summarize the observed soil and slope characteristics from the site visit:

Table B6-1: Lac Qui Parle County Soil Characteristics

Lac Qui Parle County Site Soil Characteristics	
USCS Classification	SP-SM - Poorly-graded sand with silt
SPT Correlation, N_{60} (blows / ft)	5 to 7
Moisture Content, w (%)	18.7
Undrained Shear Strength, S_u (tsf)	1.25 to 2
Effective Cohesion, c' (psf)	50
Effective Friction Angle, ϕ' (deg)	35

Table B6-2: Lac Qui Parle County Slope Characteristics

Lac Qui Parle County Slope Characteristics Summary	
Slope failure observed?	Yes
Failure type	Rotational (erosion)
Evidence / indication of failure	Visible washout failures
Water present near toe?	No
Above / below roadway?	Above
Approximate steepness	1.5H : 1V (backslope)
Observed Stabilization methods	None
Topsoil depth	1 ft

Site Report: Marshall County

Field Investigation: 8-8-2016

Marshall County is located in northwestern Minnesota, and borders North Dakota. The site is located in the eastern part of the county, between Lac Qui Parle Village and the Minnesota River. The location is shown in Figure B7-1:

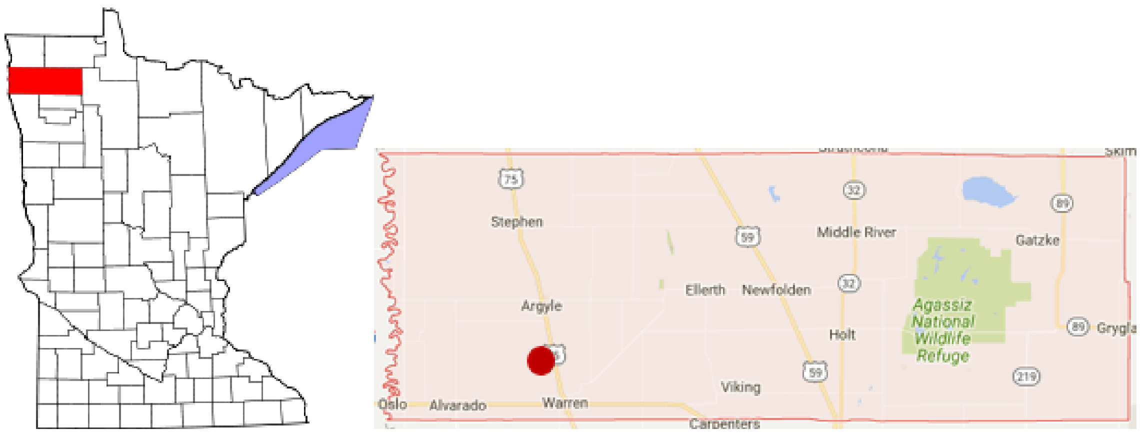


Figure B7-1: Marshall County site location

A small creek was located near the toe of the slope. An aerial photo of the site is shown in Figure B7-2.

Figure B7-2: Marshall County site aerial photo

The site's approximate UTM coordinates are 14U N 5,349,900 E 660,500. The site's topography is shown in Figure B7-3.

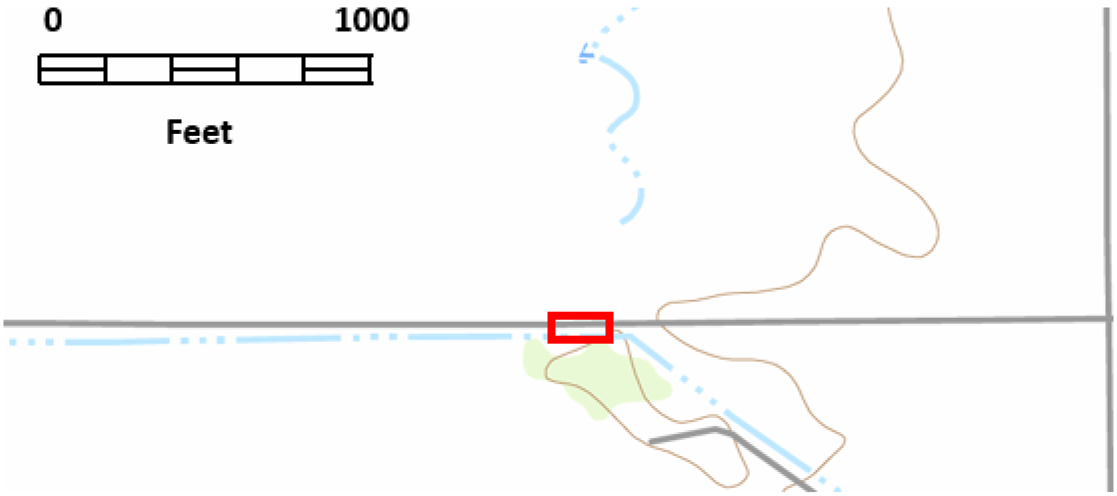


Figure B7-3: Marshall County site topography, from USGS Argyle Quadrangle, MN 7.5 Minute Map (2016)

A slope cross section is shown in Figure B7-4:

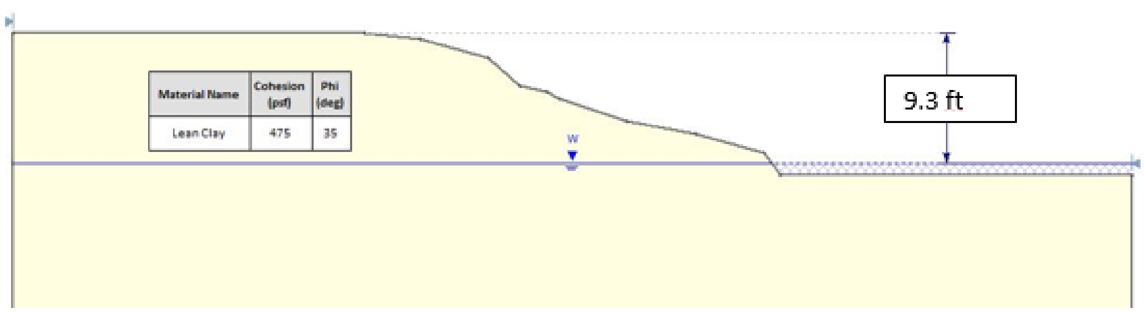


Figure B7-4: Marshall County site cross section

The following Tables describe site soil and slope characteristics.

Table B7-1: Marshall County site Soil Characteristics

Marshall County Soil Characteristics	
USCS Classification	MH - Elastic Silt
SPT Correlation, N_{60} (blows / ft)	3 to 4
Moisture Content, w (%)	21.8
Undrained Shear Strength, S_u (tsf)	1.25 to 1.75
Effective Cohesion, c' (psf)	600
Effective Friction Angle, ϕ' (deg)	18

Table B7-2: Marshall County site Slope Characteristics

Marshall County Slope Characteristics Summary	
Slope failure observed?	Yes
Failure type	Creep
Evidence / indication of failure	Visible soil movement
Water present near toe?	yes
Above / below roadway?	below
Approximate steepness	2.5H:1V
Observed Stabilization methods	N/A
Topsoil depth	1 ft

Site Report: Murray County

Field Investigation: 11-12-2015

Murray County is located in the southwestern part of the state. The site is located in the northeast corner of the county, south of Walnut Grove, Minnesota. The site location is shown in Figure B8-1:

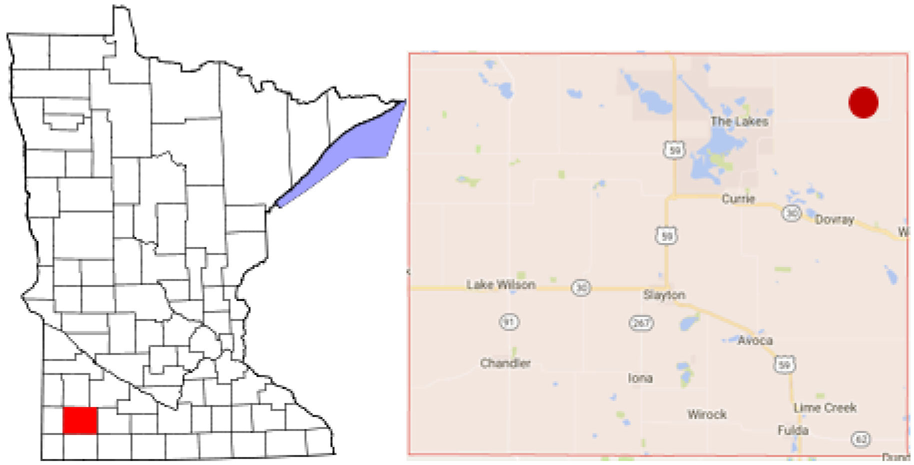


Figure B8-1: Murray County site location

The site is on a culvert over the Plum Creek, so water is present near the toe of the slope. Figure B8-2 shows an aerial photo of the site and surrounding features:

Figure B8-2: Murray County site aerial photo

The site's approximate UTM coordinates are 15T N 4,895,100 E 300,050. Topography and site location are shown in Figure B8-3. The site is located where the road crosses the Plumb Creek.

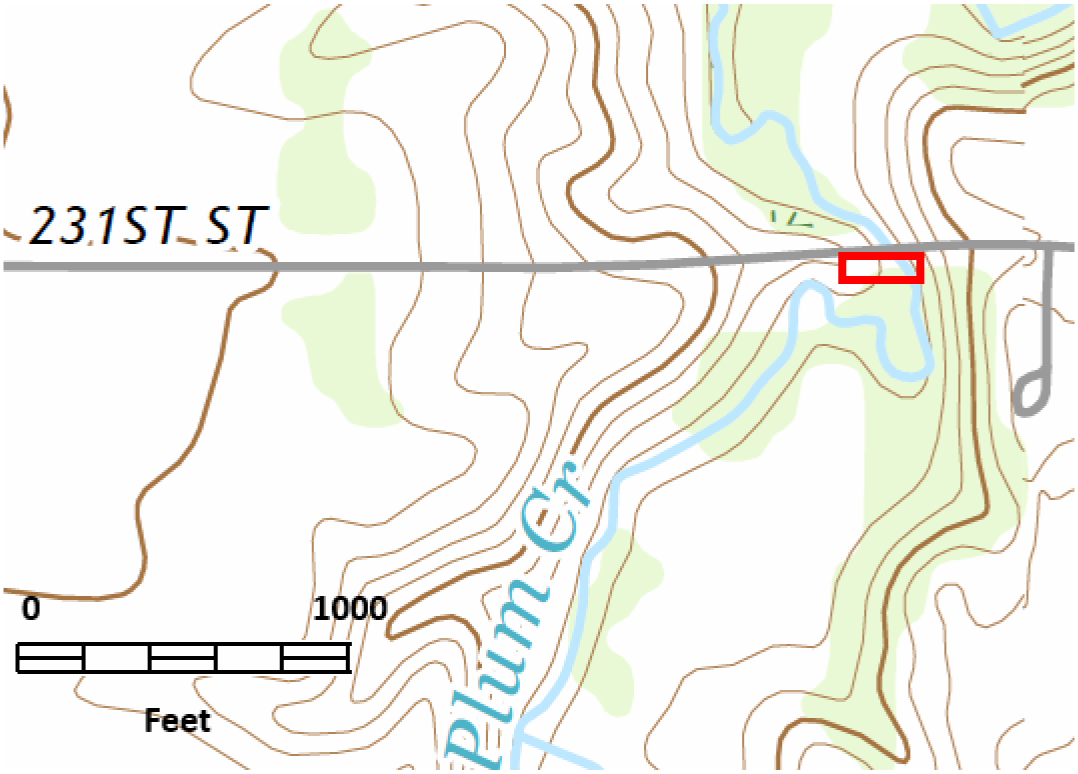


Figure B8-3: Murray County site topography, from USGS Tracy East Quadrangle, MN 7.5 Minute Map (2016)

Site geometry was not measured, because the slope was reconstructed for repairs. Figure B8-4 shows a cross section from the reconstruction plans, provided by the county highway department:

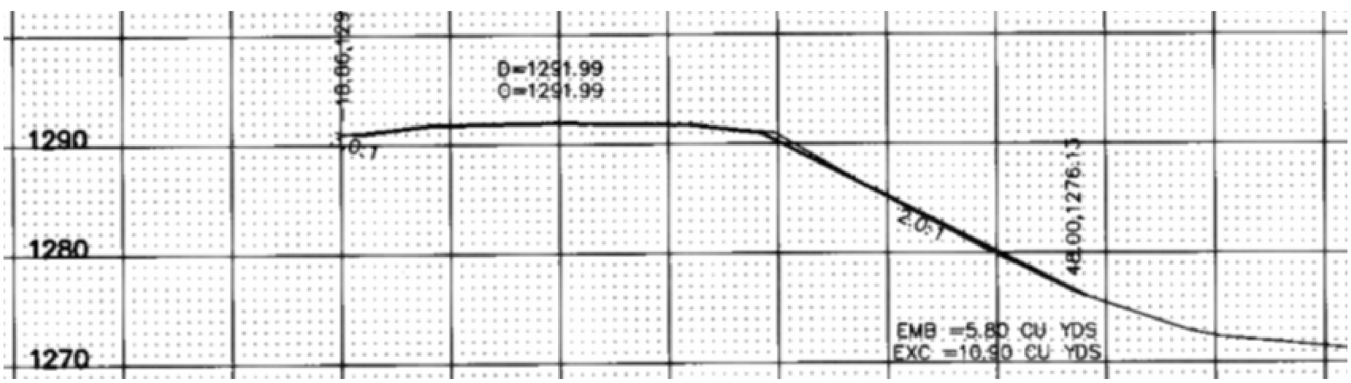


Figure B8-4: Murray County site geometry

The following tables summarize observed characteristics of the soil and slope:

Table B8-1: Murray County Soil (Native) Characteristics

Murray County Site Native Soil Characteristics	
USCS Classification	ML - Sandy silt
SPT Correlation, N_{60} (blows / ft)	3 to 4
Moisture Content, w (%)	30.6
Undrained Shear Strength, S_u (tsf)	not tested
Effective Cohesion, c' (psf)	900
Effective Friction Angle, ϕ' (deg)	22

Table B8-2: Murray County Soil (Fill) Characteristics

Murray County Site Fill Soil Characteristics	
USCS Classification	SC - Clayey Sand
SPT Correlation, N_{60} (blows / ft)	3 to 4
Moisture Content, w (%)	30.6
Undrained Shear Strength, S_u (tsf)	not tested
Effective Cohesion, c' (psf)	390
Effective Friction Angle, ϕ' (deg)	32

Table A8-3: Murray County Slope Characteristics

Murray County Slope Characteristics Summary	
Slope failure observed?	Yes (repaired)
Failure type	Creep at top of slope
Evidence / indication of failure	Pavement distress
Water present near toe?	Yes (Plumb Creek)
Above / below roadway?	Below
Approximate steepness	2H : 1V
Observed Stabilization methods	Remove and Replace
Topsoil depth	0.5 to 1 ft

Site Report: Olmsted County

Field Investigation: 11-24-2015

Olmsted County is located in the southeast part of the state. The site is located in the western part of the county, southwest of Rochester, MN. The site location is shown in Figure B9-1:

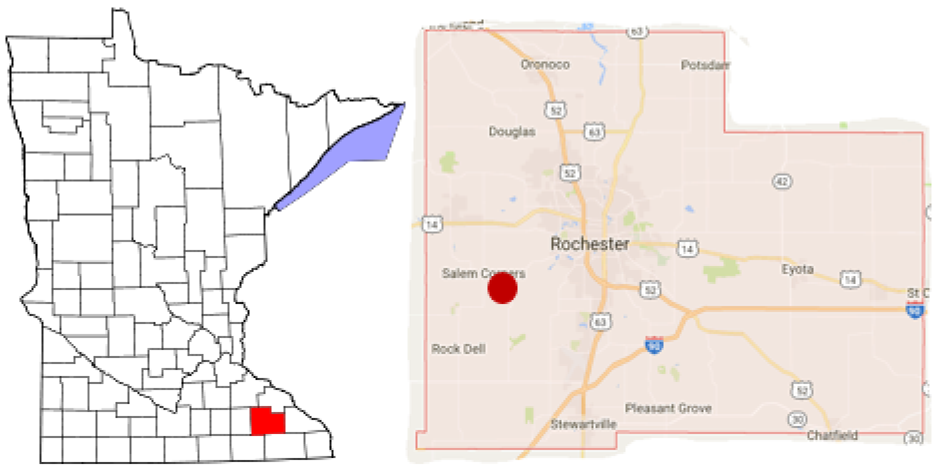


Figure B9-1: Olmsted County location

No bodies of water are near the slope. Figure B9-2 shows an aerial photo of the site and surrounding features:

Figure B9-2: Olmsted County site aerial photo

The site's approximate UTM coordinates are 15T N 4,867,200 E 533,950. Site topography and approximate location are shown in Figure B9-3:

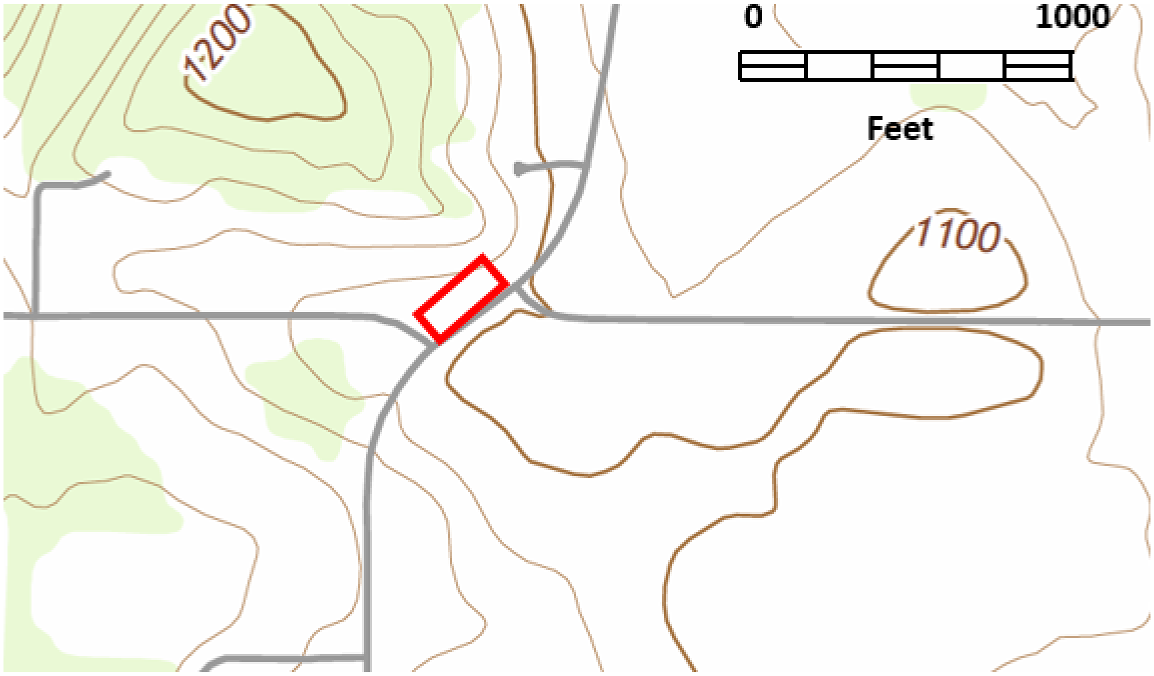


Figure B9-3: Olmsted County site topography, from USGS Salem Corners Quadrangle, MN 7.5 Minute Map (2016)

The slope geometry was also determined, and a SLIDE model was produced. Figure B8-4 shows the model cross section. The slope has an overall steepness of approximately 3H:1V. Figure B9-5 shows a cross section from the failed area.

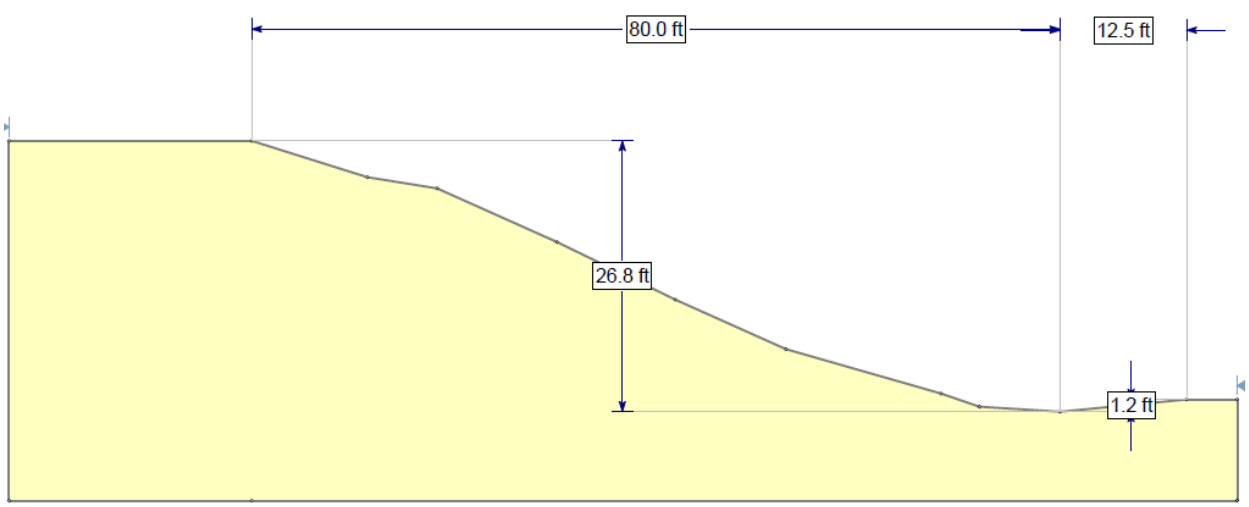


Figure B9-4: Olmsted County site geometry

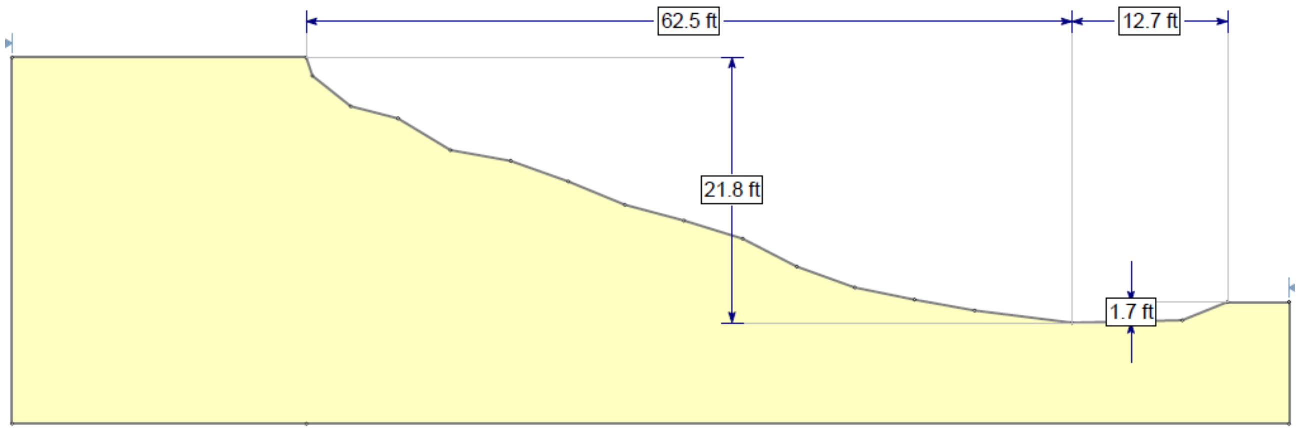


Figure B9-5: Olmsted County slope geometry, failed section

The following tables summarize the observed characteristics at the site.

Table B9-1: Olmsted County Soil Characteristics

Olmsted County Site Soil Characteristics	
USCS Classification	CL - Sandy lean clay
SPT Correlation, N_{60} (blows / ft)	3
Moisture Content, w (%)	16.8
Undrained Shear Strength, S_u (tsf)	0.25 to 0.5
Effective Cohesion, c' (psf)	200
Effective Friction Angle, ϕ' (deg)	34

Table B9-2: Olmsted County Slope Characteristics

Olmsted County Slope Characteristics Summary	
Slope failure observed?	Yes
Failure type	Rotational and creep

Evidence / indication of failure	Visible scarp on face
Water present near toe?	No
Above / below roadway?	Above
Approximate steepness	3H : 1V
Observed Stabilization methods	None
Topsoil depth	0.5 to 1 ft

Site Report: Pennington County

Field Investigation 8-8-2016

Pennington County is located in the northwest part of the state, near North Dakota. The site is located in the central part of the county, south of Thief River Falls, MN. The site location is shown in Figure B10-1.

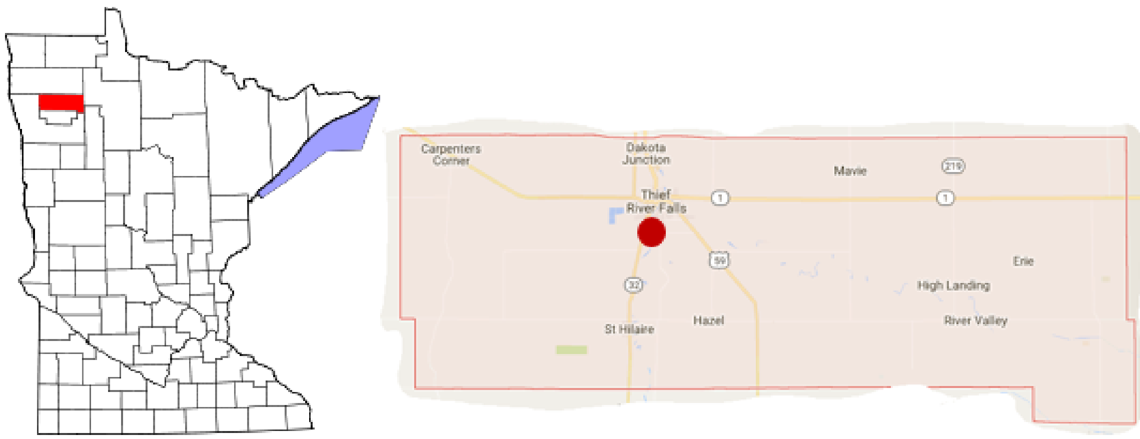


Figure B10-1: Pennington County site location

Researchers noted standing water at the toe of the slope. An aerial photo of the site is shown in Figure B10-2.

Figure B10-2: Aerial photo of Pennington County site

The site's approximate UTM coordinates are 14U N 5,328,200 E 708,400. Site topography is shown in Figure B10-3.

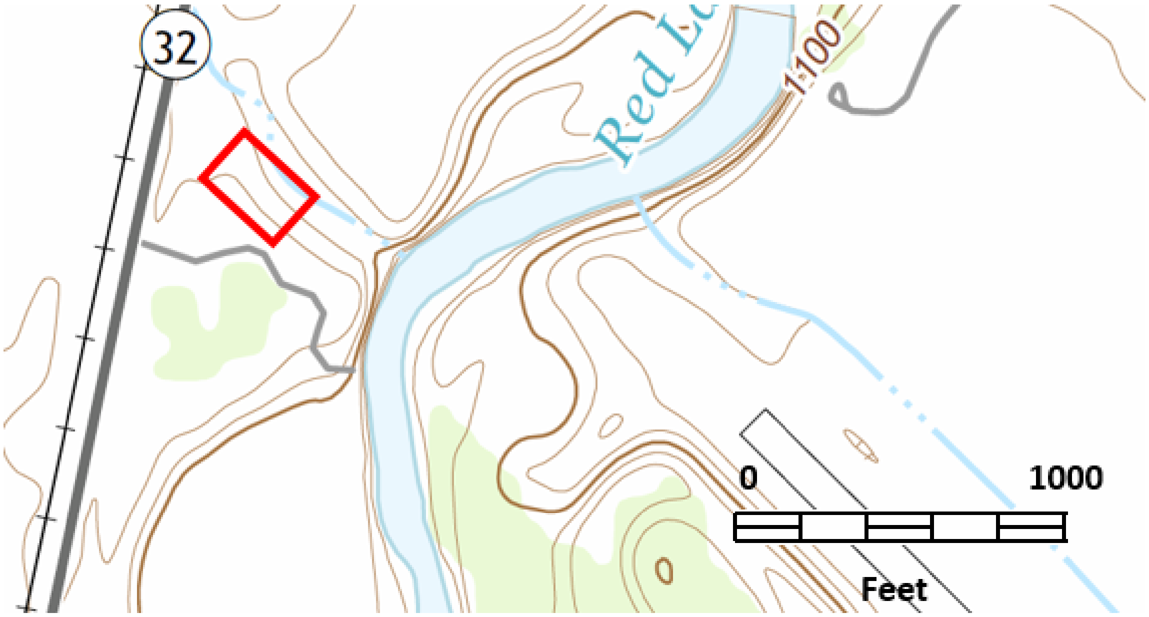


Figure B10-3: Pennington County site topography, from USGS Thief River Falls Quadrangle, MN 7.5 Minute Map (2016)

A cross section of the site is provided in Figure B10-4.

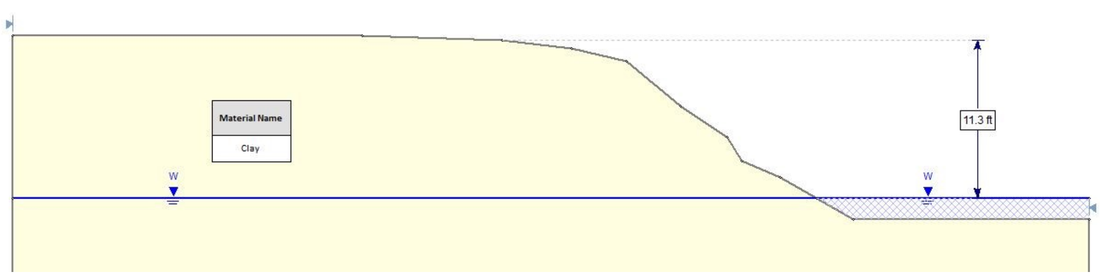


Figure B10-4: Pennington County site cross section

Observed soil and slope characteristics on site are summarized in the following tables:

Table B10-1: Pennington County soil characteristics

Pennington County Site Soil Characteristics	
USCS Classification	ML - Silt with sand
SPT Correlation, N_{60} (blows / ft)	3 to 4
Moisture Content, w (%)	26.5
Undrained Shear Strength, S_u (tsf)	0.25 to 0.75
Effective Cohesion, c' (psf)	1275
Effective Friction Angle, ϕ' (deg)	17

Table BA10-2: Pennington County slope characteristics

Pennington County Slope Characteristics Summary	
Slope failure observed?	Yes
Failure type	Rotational
Evidence / indication of failure	Clearly visible failure surface
Water present near toe?	yes
Above / below roadway?	below
Approximate steepness	1.5H:1V
Observed Stabilization methods	N/A
Topsoil depth	1 ft

Site Report: Redwood County

Field Investigation: 11-12-2015

Redwood County is located in southwest Minnesota, along the Minnesota River. The site is in the northeast part of the county, approximately one mile south of Franklin, Minnesota. The location is summarized in Figure B11-1:

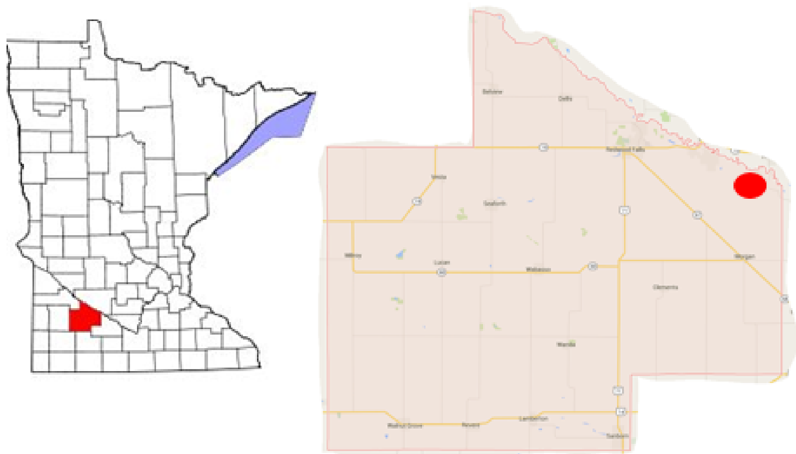


Figure B11-1: Redwood County site location

The Minnesota River is near the toe of the slope. The site, river, and surrounding features are shown in the aerial photo in Figure B11-2:

Figure B11-2: Redwood County site aerial photo

The center of the investigation area has the following approximate UTM coordinates: 15T N 4,929,900 E 350,200. Site topography and approximate location are shown in Figure B11-3:

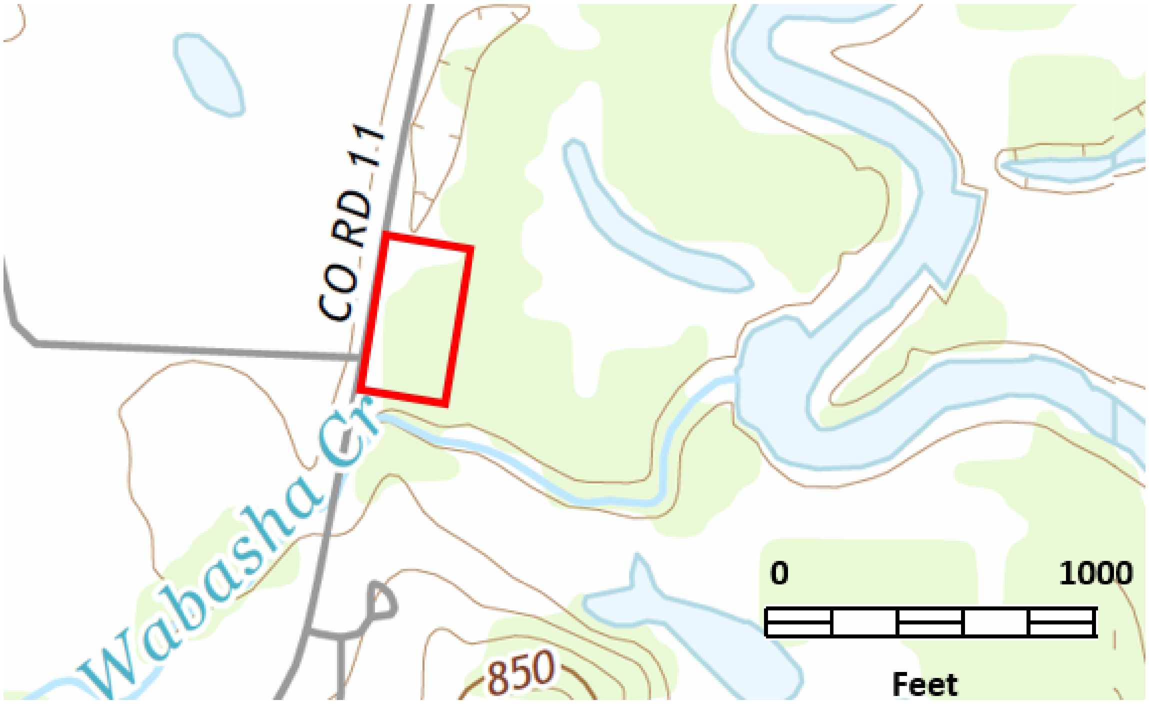


Figure B11-3: Redwood County site topography, from USGS Morton Quadrangle, MN 7.5 Minute Map (2016)

A typical cross section is shown in Figure B11-4:

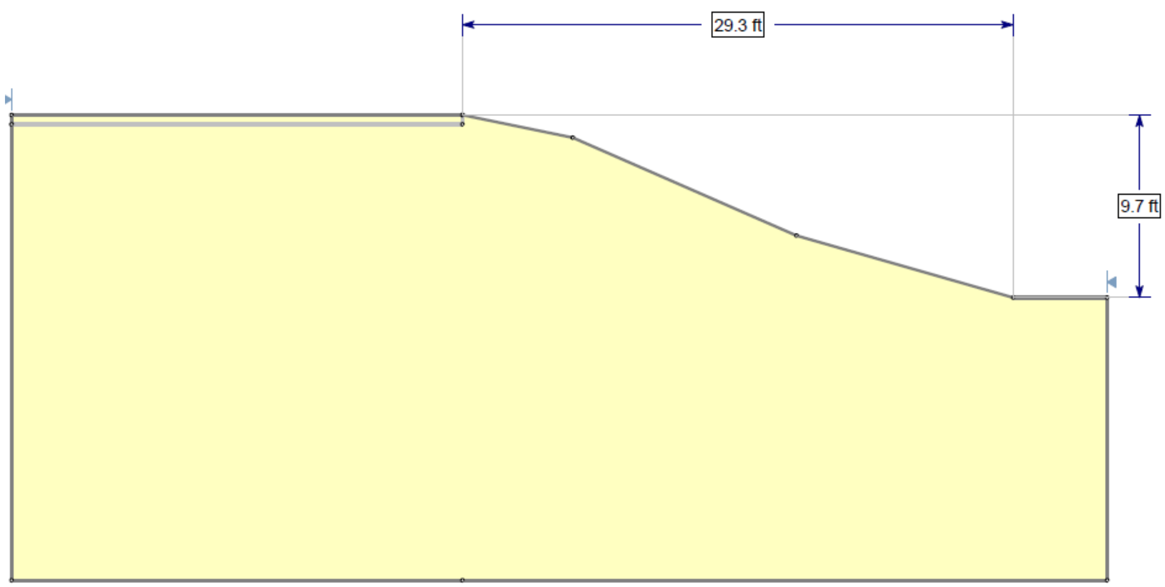


Figure B11-4: Redwood County site geometry

Observed soil and slope characteristics on site are summarized in the following tables:

Table B11-1: Redwood County Soil Characteristics

Redwood County Site Soil Characteristics	
USCS Classification	CH - Fat clay with sand
SPT Correlation, N_{60} (blows / ft)	4 to 5
Moisture Content, w (%)	36.0
Undrained Shear Strength, S_u (tsf)	0.5
Effective Cohesion, c' (psf)	750
Effective Friction Angle, ϕ' (deg)	21

Table B11-2: Redwood County Slope Characteristics

Redwood County Slope Characteristics Summary	
Slope failure observed?	No (repaired)
Failure type	N/A
Evidence / indication of failure	Pavement distress, Rip Rap cover
Water present near toe?	Yes - Minnesota River
Above / below roadway?	Below
Approximate steepness	3H : 1V
Observed Stabilization methods	Rip Rap cover, geosynthetics
Topsoil depth	0.5 ft

Site Report: St. Louis County

Field Investigation: 11-10-2015

St. Louis County is located in the northeast part of the state. The site is located in the northwest part of the county, near the border with Koochiching and Itasca Counties. The location is show in Figure B12-1:

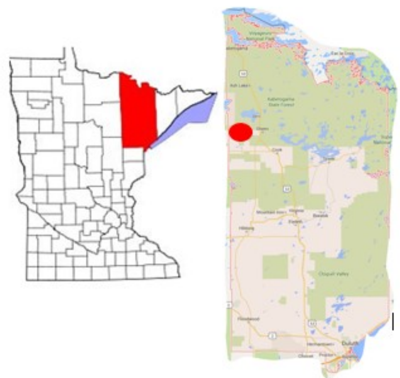


Figure B12-1: St. Louis County site location

The Littlefork River is located near the toe of the slope. A drainage culvert failure appears to be the cause of the failure. An aerial photo of the site is shown in Figure B12-2:

Figure B12-2: St. Louis County site location

The site has the following approximate UTM coordinates: 15T N 5,307,250 E 494,000. Site topography and location are shown in Figure B12-3. The site is located where a small stream feeds into the Littlefork River.

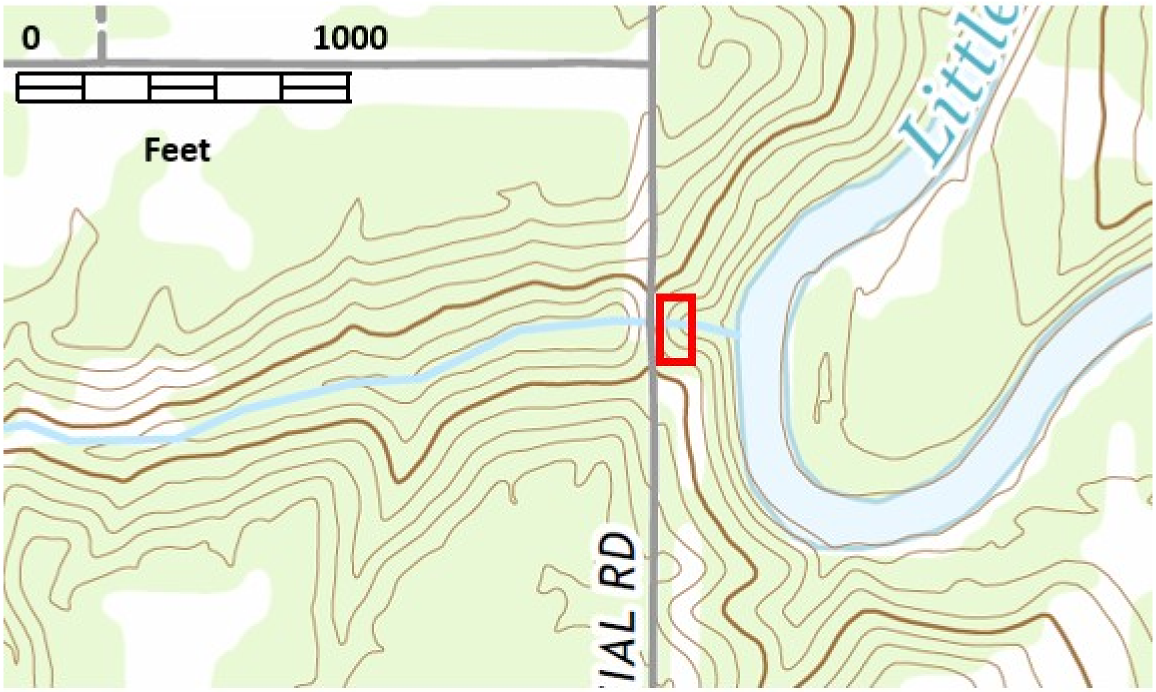


Figure B12-3: St. Louis County site topography, from USGS Silverdale Quadrangle, MN 7.5 Minute Map (2016)

The site failure was severe, so researchers did not measure the slope profile. The site was eventually disregarded as a case study for in-house stabilization of common slope failures.

Site Report: Washington County

Field Investigation: 11-23-2015

Washington County is located in the eastern part of the seven county metro area, and borders Wisconsin. The site is located in the south part of the county, approximately one mile south of Afton, Minnesota. The site location is summarized in Figure B13-1:

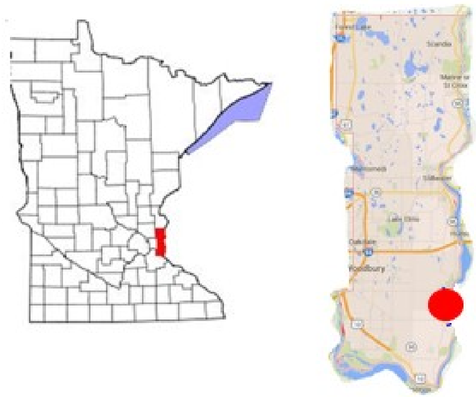


Figure B13-1: Washington County site location

No bodies of water were located near the toe of the slope. Investigators performed limited field investigation because the site had already been repaired full-scale slope repair. An aerial photo of the site is shown in Figure B13-2:

Figure B13-2: Washington County site aerial photo

The site's approximate UTM coordinates are 15T N 4,970,950 E 516,900. Site topography and location are shown in Figure B13-3:

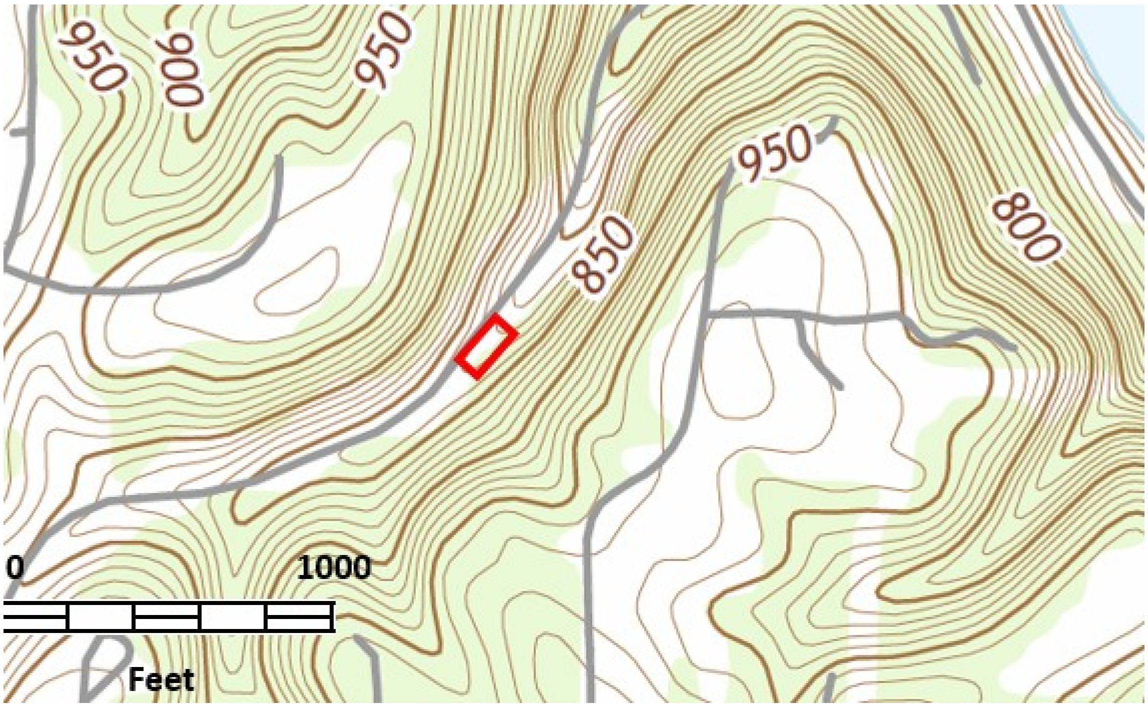


Figure B13-3: Washington County site topography, from USGS Hudson Quadrangle, MN-WI 7.5 Minute Map (2016)

Slope Geometry was not measured, because a geotechnical report is available for the site. Figure B11-4 shows the slope geometry from a report provided by the county engineer.

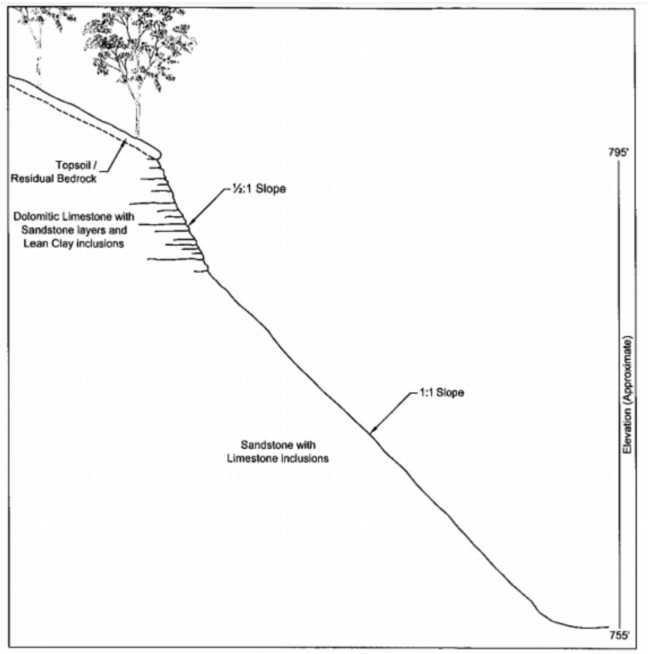


Figure B13-4: Washington County Site slope profile (from Washington Co. Highway Dept.)

The severity of failure and repair excluded this site from further consideration as a case study.

APPENDIX C: DNR GROUNDWATER MONITORING WELLS FOR CASE STUDY SITES

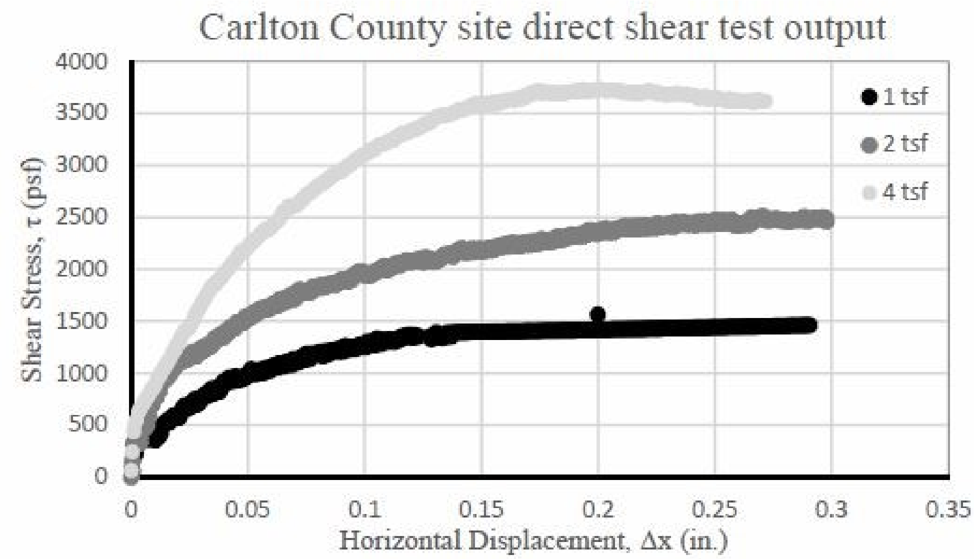
Provided is a list of DNR groundwater monitoring wells; listed are the well numbers, and each corresponding site. Few sites had monitoring wells near the slope. Groundwater monitoring data is available at:

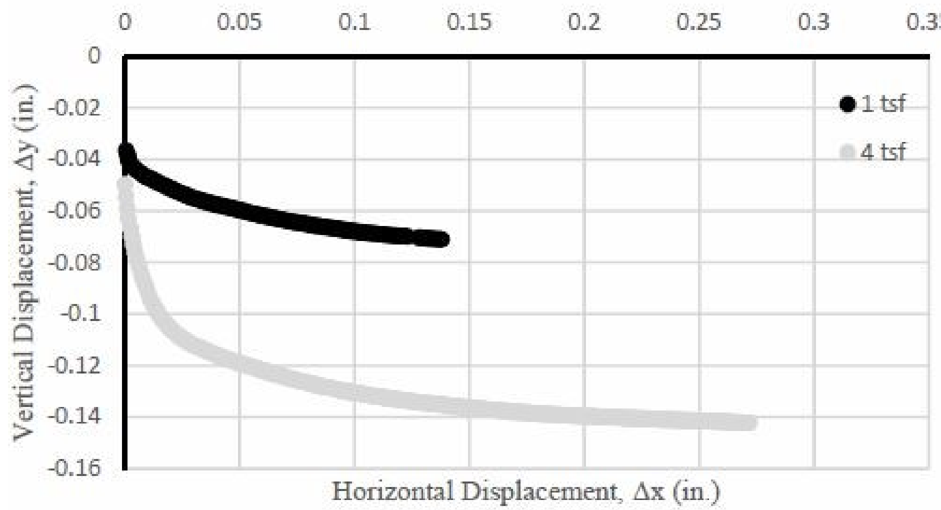
http://www.dnr.state.mn.us/waters/cgm/index.html

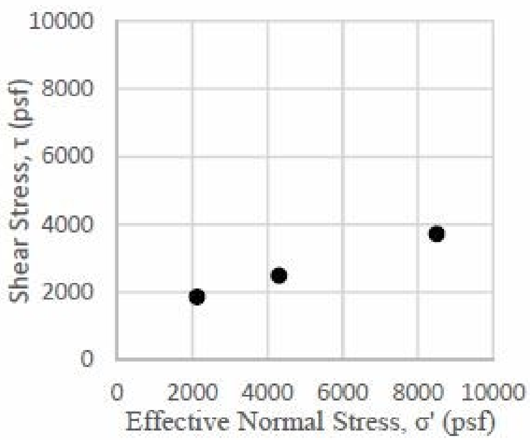
Site	**DNR Observation Well Number**
Carlton Co.	9030
Carver Co.	70020
Fillmore Co.	23001
Houston Co.	23002
Koochiching Co.	36000
Lac Qui Parle Co.	37007
Marshall Co.	45001
Murray Co.	64000
Olmsted Co.	55001
Pennington Co.	57001
Redwood Co.	64002
St. Louis Co.	31001
Washington Co.	82063

APPENDIX D: SOIL STRENGTH CHARACTERIZATION DATA

This Appendix provides raw results from the direct shear test. Each sample was tested at three confining stresses: 1 tsf, 2 tsf, and 4 tsf. The author used the plot of horizontal displacement vs. shear stress to identify the maximum shear stress for each test. Plotting the maximum shear stress vs. the corresponding normal stress allowed the calculation of c' and ϕ'. The vertical displacement outputs are also provided to indicate each sample's shear behavior.

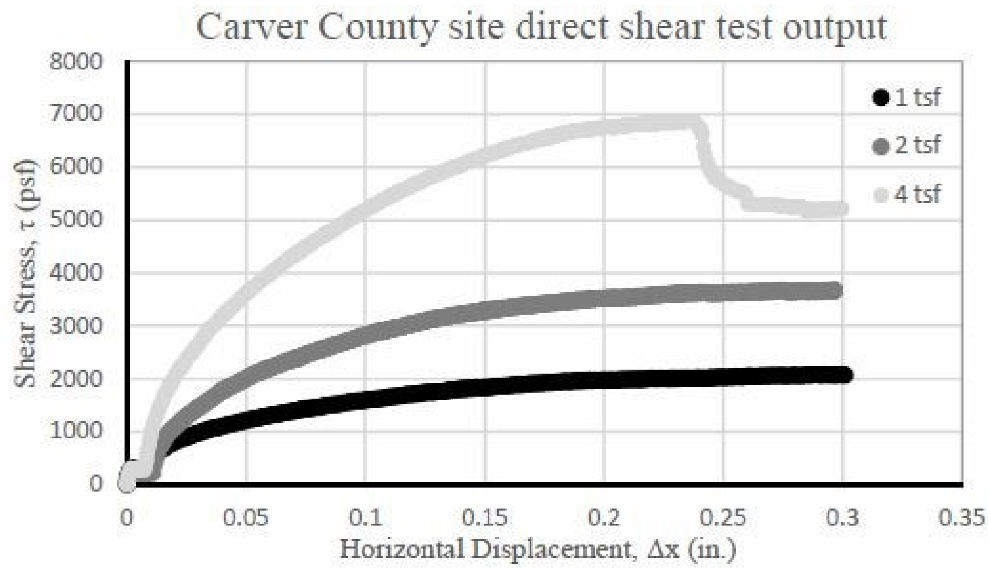


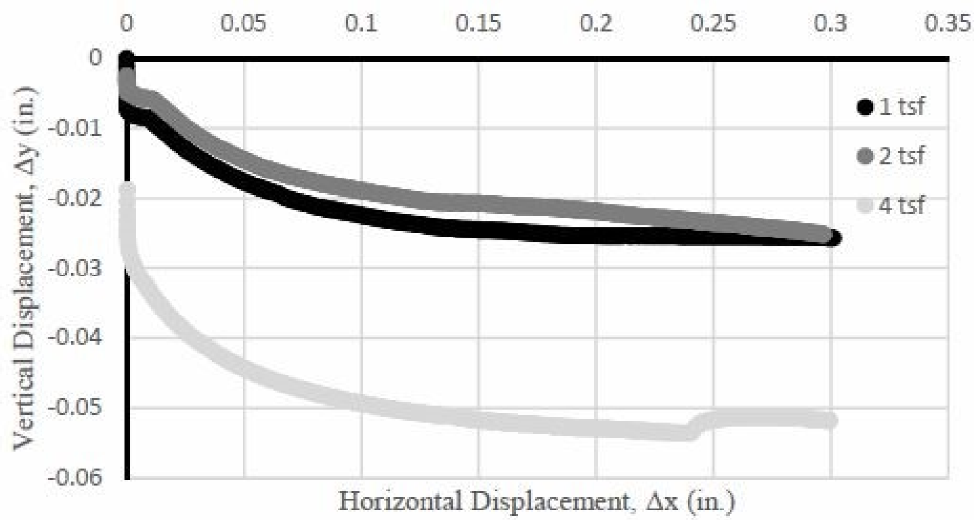


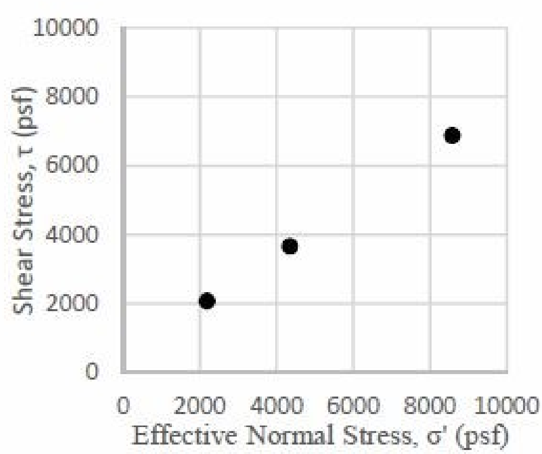


φ' (deg)	16
c' (psf)	1220
S_u (tsf)	1.25 to 1.5
DCP blows per ft.	2

Figure D1: Carlton County site strength characterization data

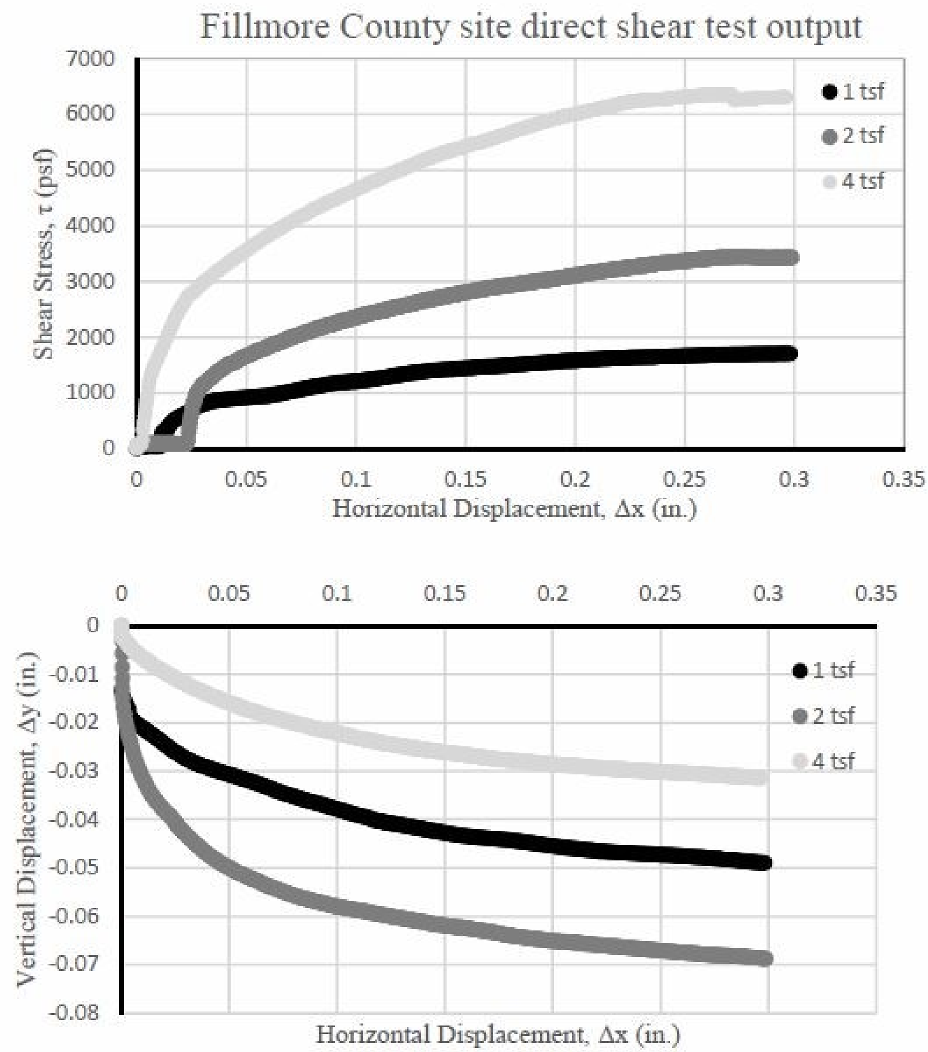


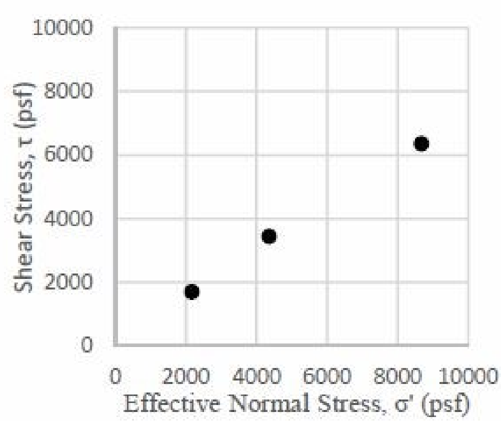




φ' (deg)	35
c' (psf)	200
S_u (tsf)	0.5 to 0.75
DCP blows per ft.	3 to 4

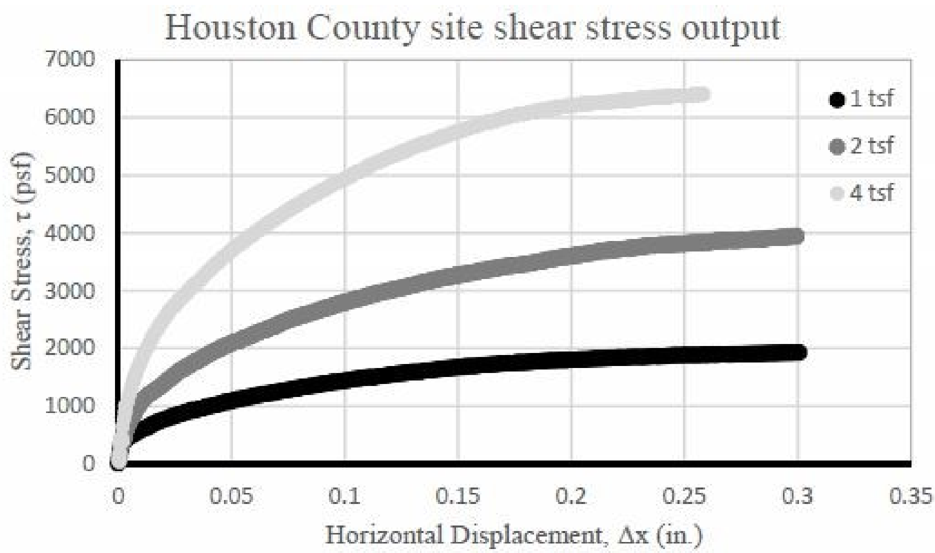
Figure D2: Carver County site strength characterization data

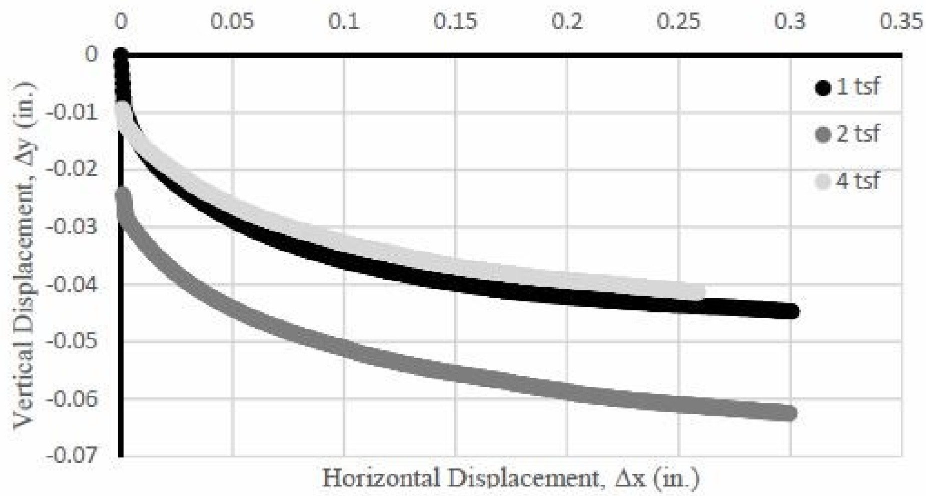


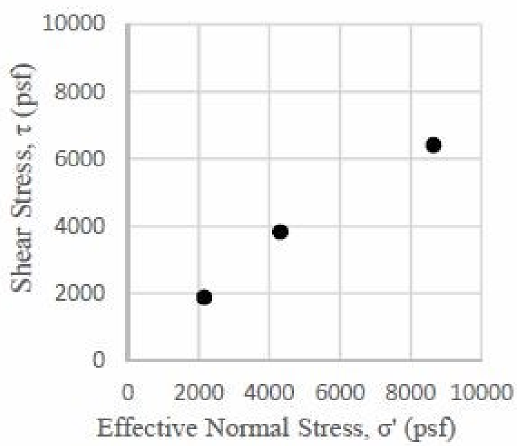


φ' (deg)	35
c' (psf)	150
S_u (tsf)	1.25 to 1.75
DCP blows per ft.	4 to 5

Figure D3: Fillmore County site strength characterization data

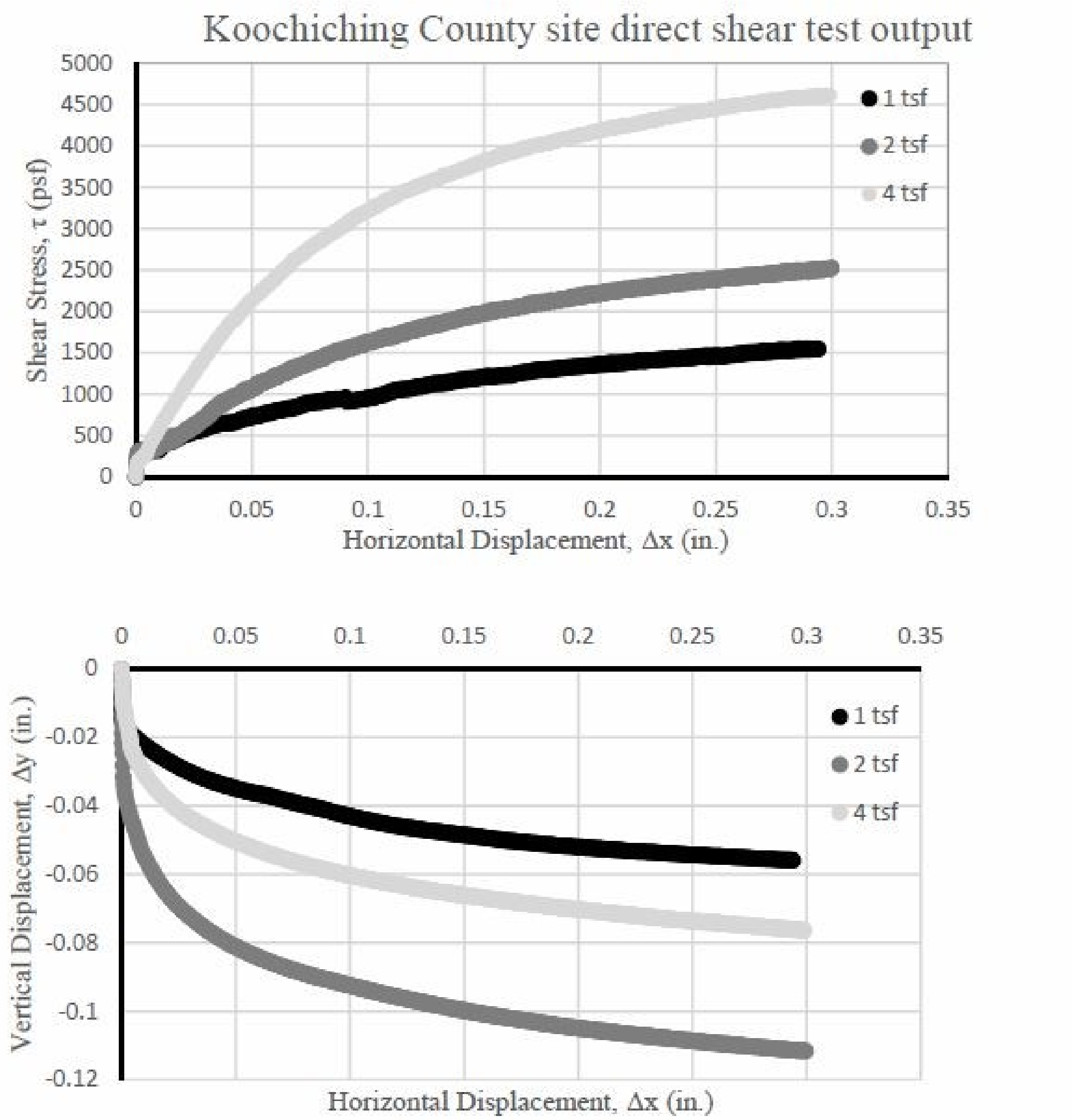


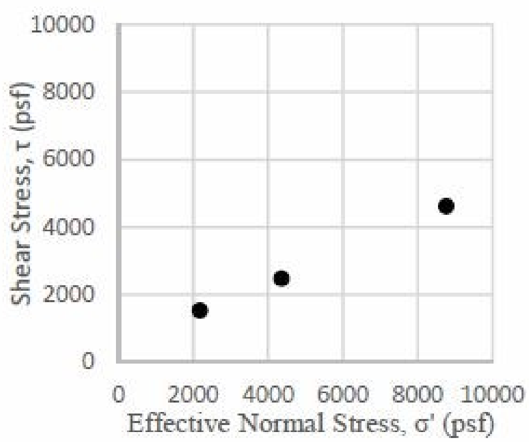




φ' (deg)	34
c' (psf)	300
S_u (tsf)	N/A
DCP blows per ft.	N/A

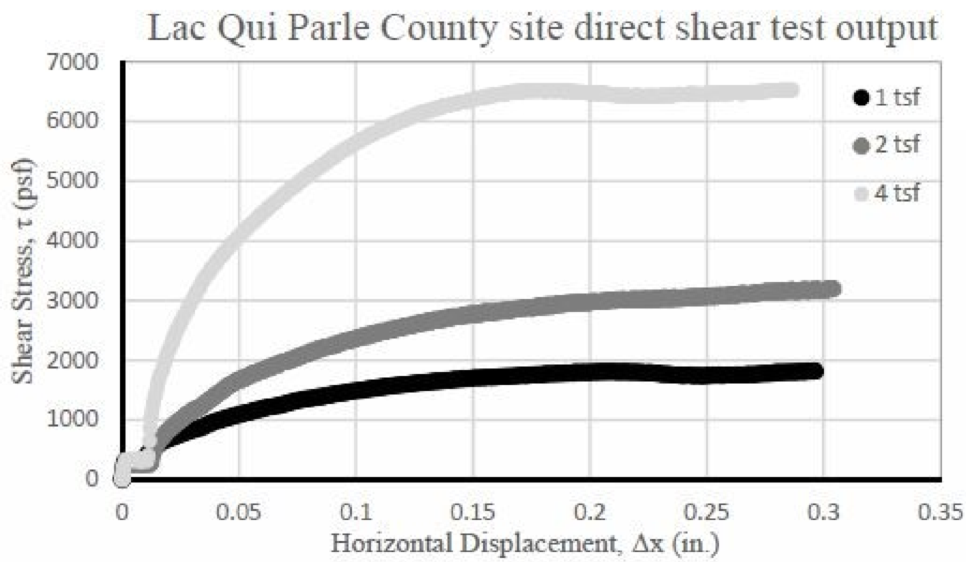
Figure D4: Houston County site strength characterization data

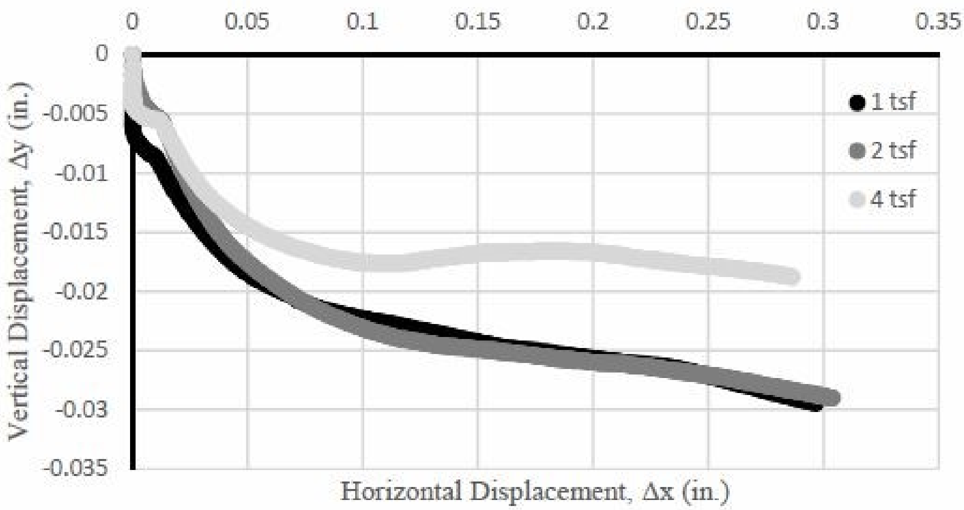


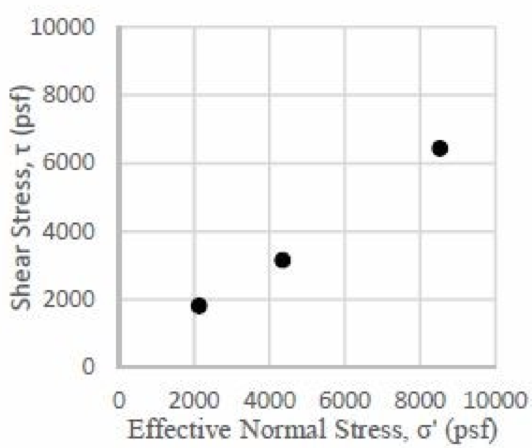


φ' (deg)	24
c' (psf)	400
S_u (tsf)	1 to 1.5
DCP blows per ft.	5

Figure D5: Koochiching County site strength characterization data

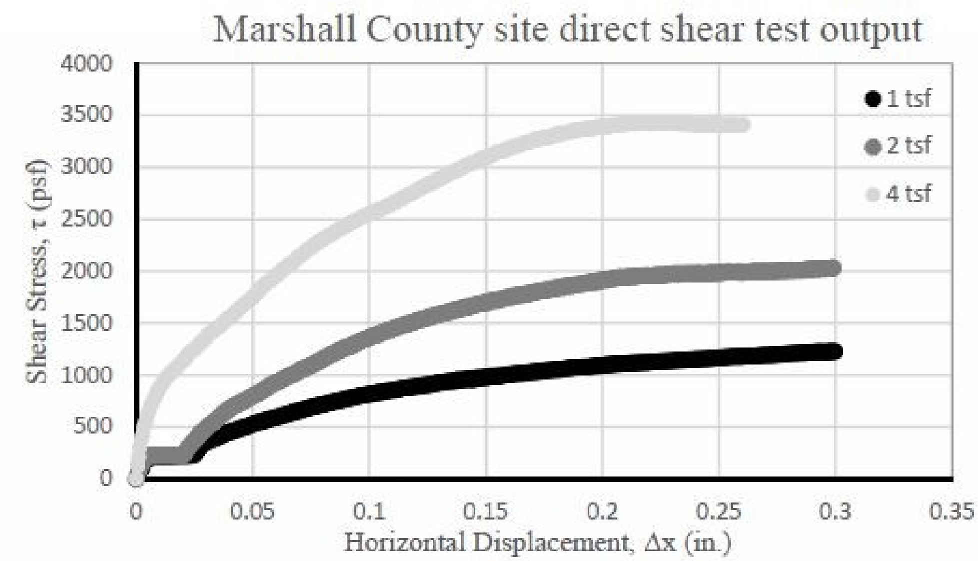


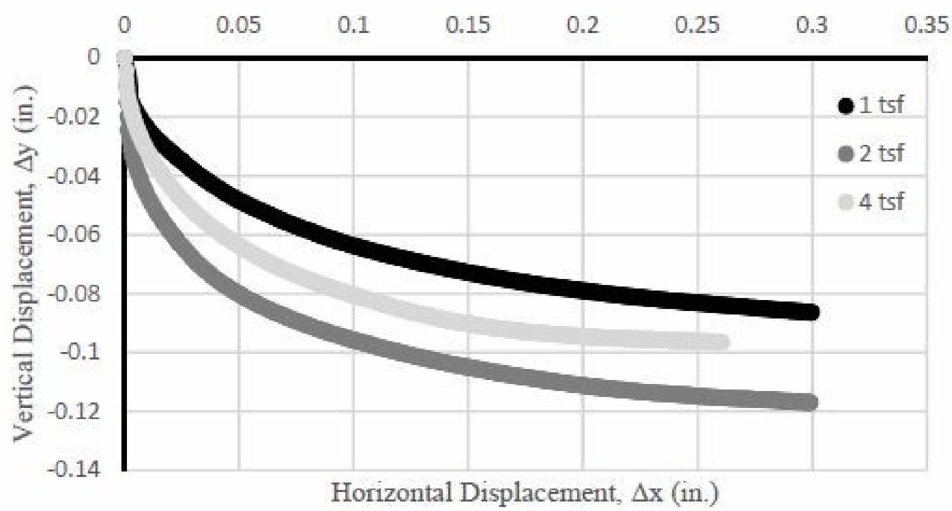


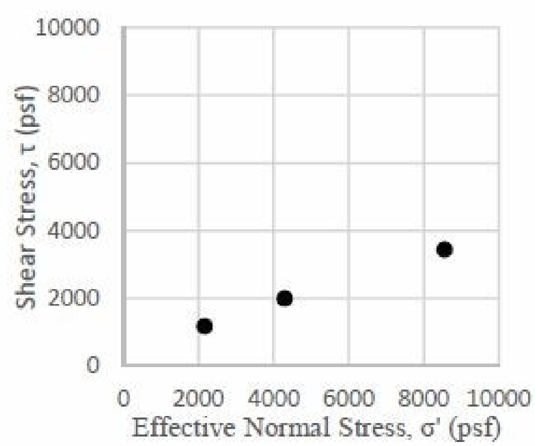


φ' (deg)	35
c' (psf)	50
S_u (tsf)	1.25 to 2
DCP blows per ft.	5 to 7

Figure D6: Lac qui Parle County site strength characterization data

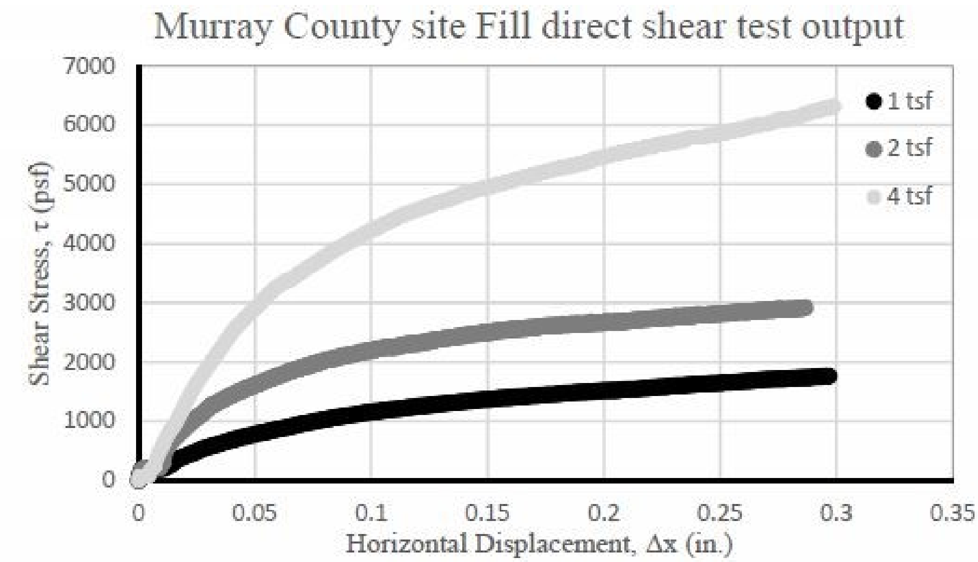


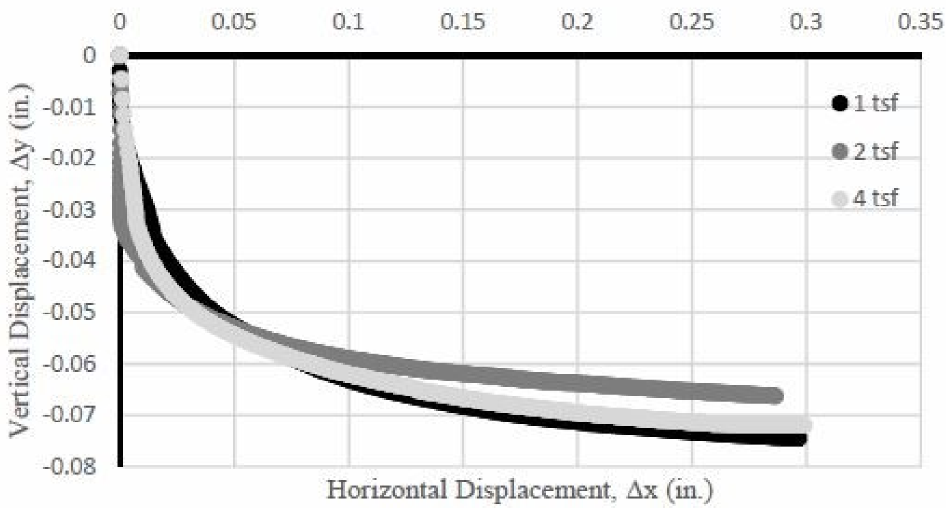


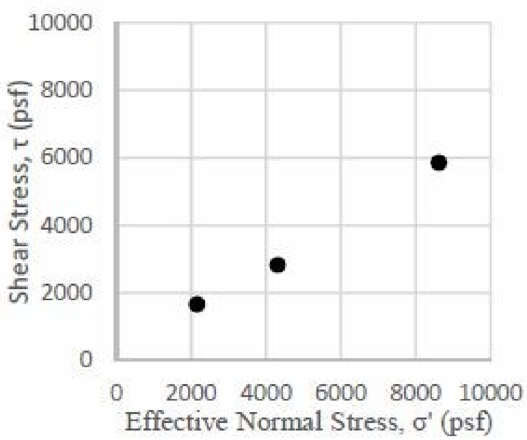


φ' (deg)	18
c' (psf)	600
S_u (tsf)	1.25 to 1.75
DCP blows per ft.	3 to 4

Figure D7: Marshall County site strength characterization data

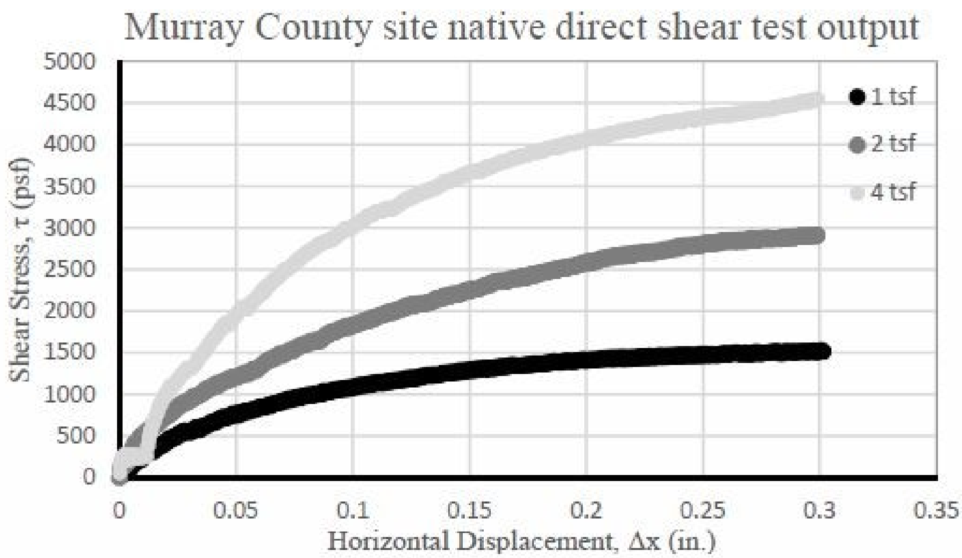


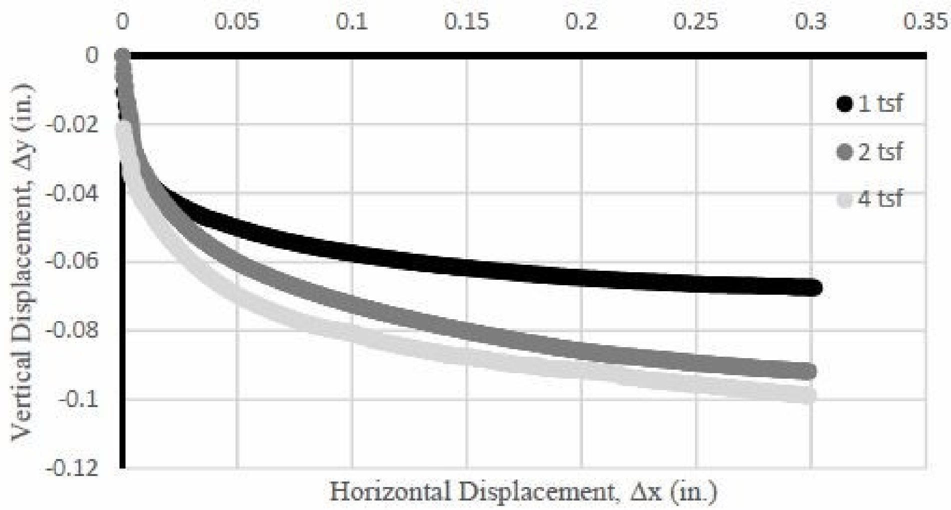


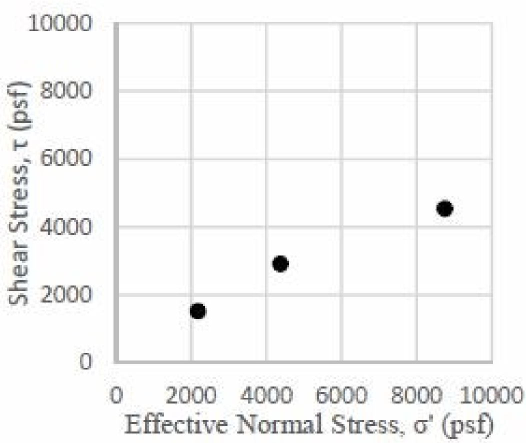


φ' (deg)	32
c' (psf)	390
S_u (tsf)	N/A
DCP blows per ft.	3 to 4

Figure D8: Murray County site fill strength characterization data

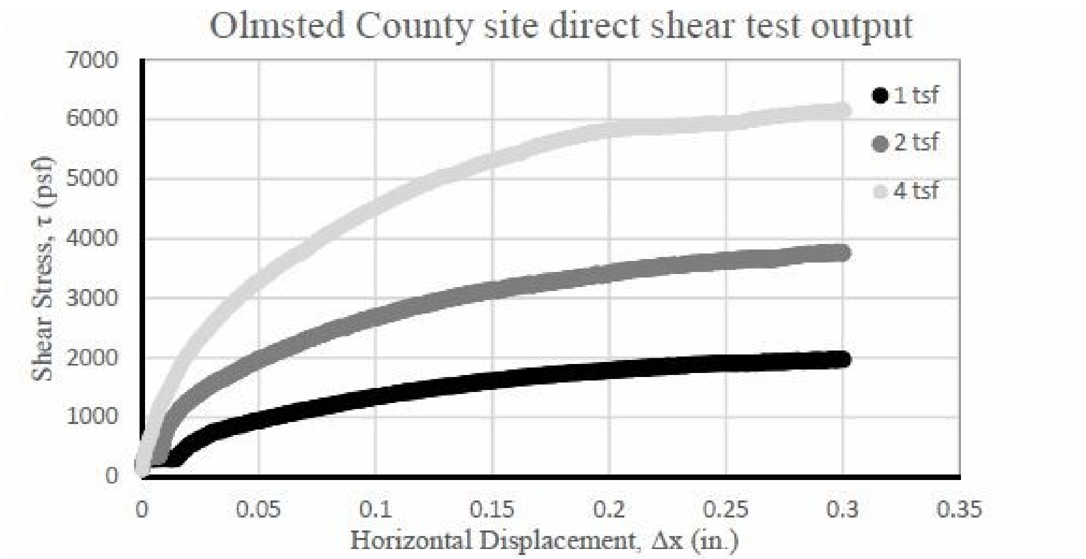


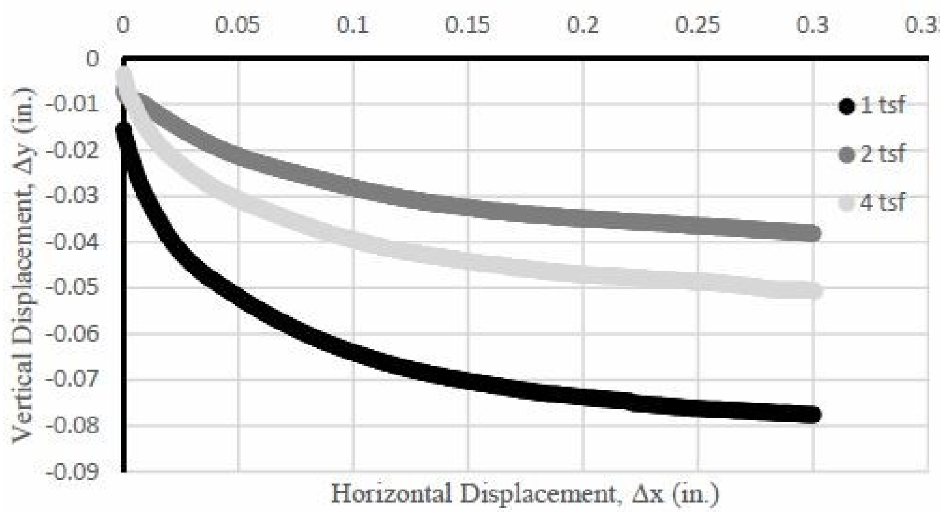


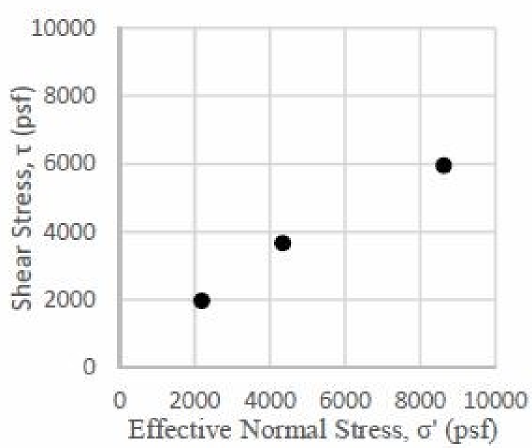


φ' (deg)	22
c' (psf)	900
S_u (tsf)	N/A
DCP blows per ft.	3 to 4

Figure D9: Murray County site native strength characterization data

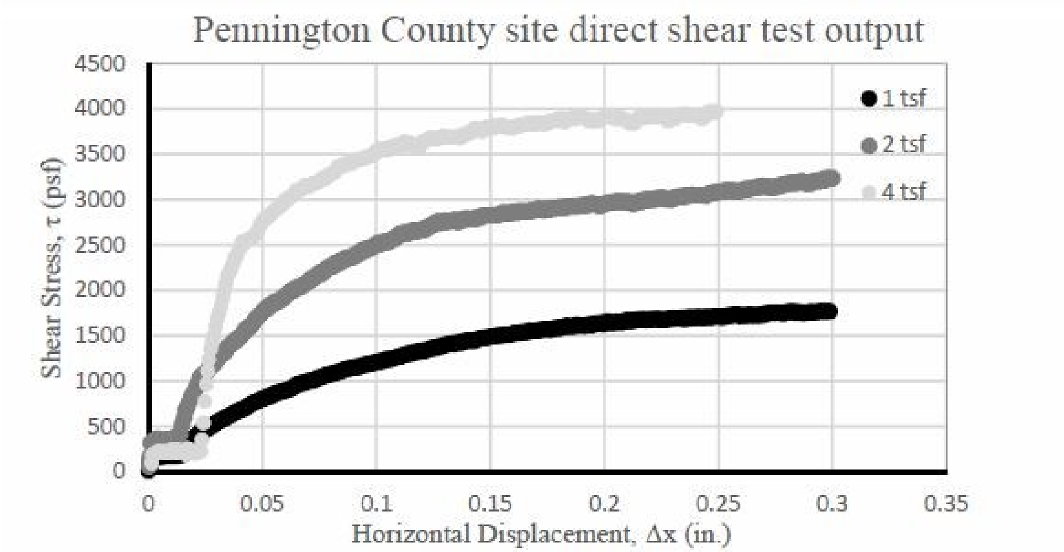


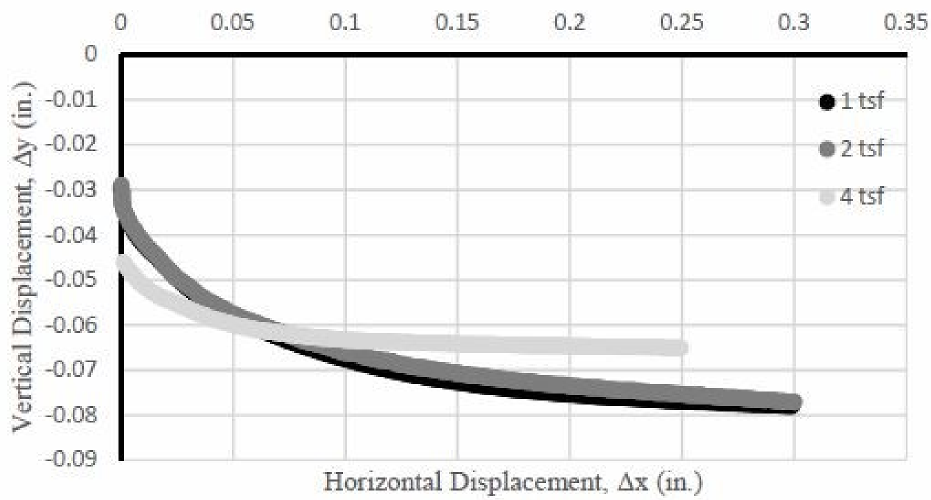


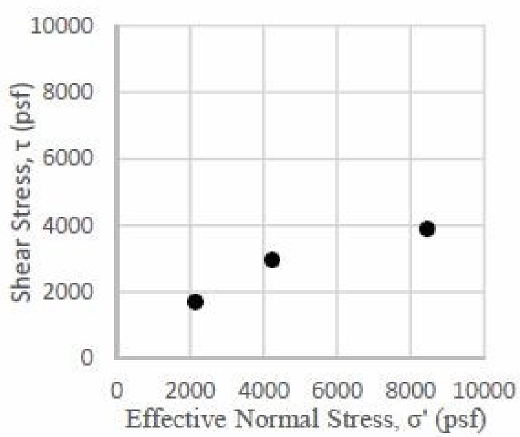


φ' (deg)	34
c' (psf)	200
S_u (tsf)	0.25 to 0.5
DCP blows per ft.	3

Figure D10: Olmsted County site strength characterization data

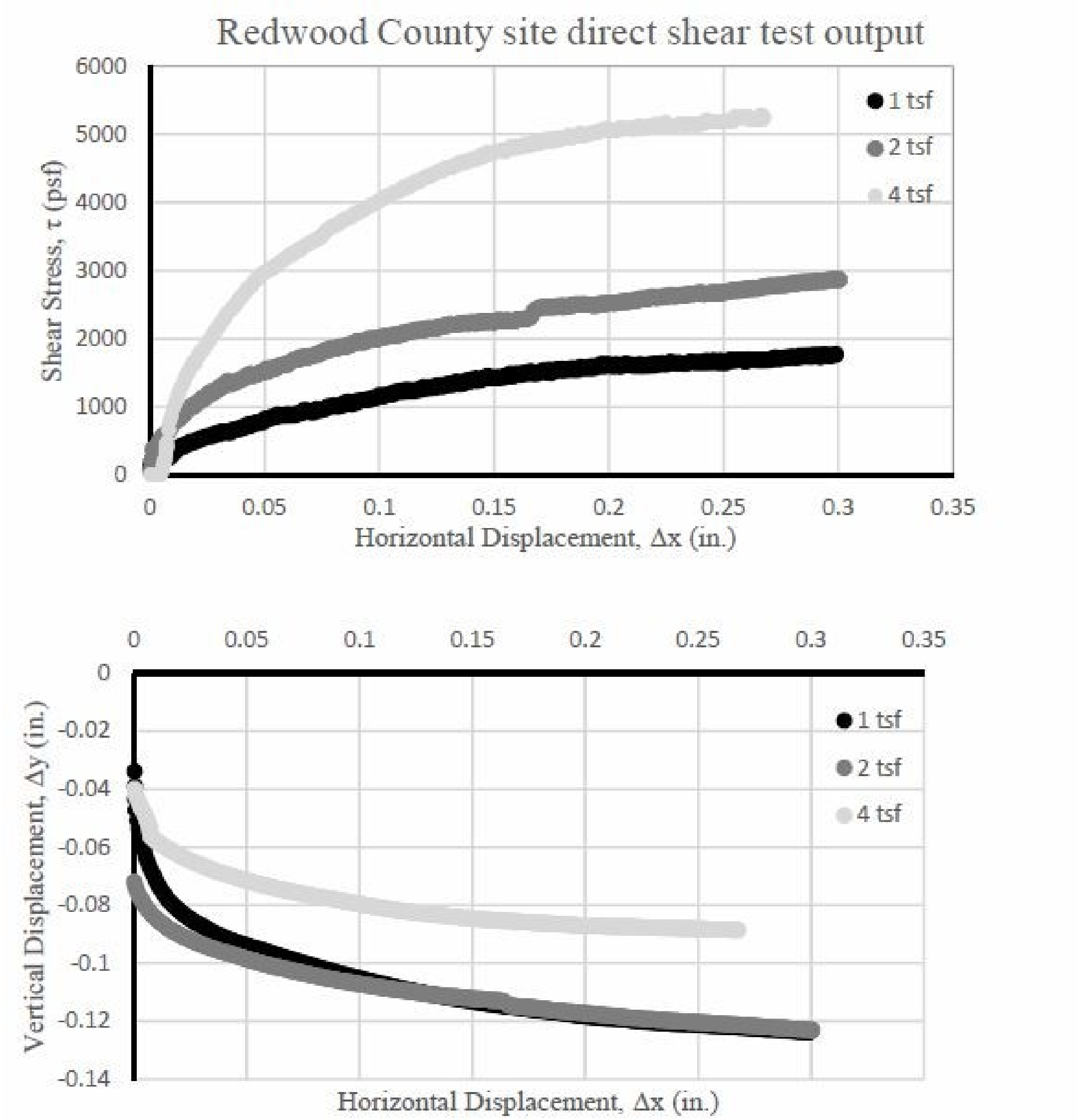


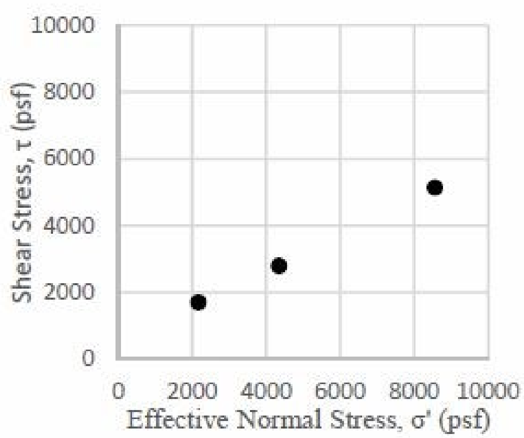




φ' (deg)	17
c' (psf)	1275
S_u (tsf)	0.25 to 0.75
DCP blows per ft.	3 to 4

Figure D11: Pennington County site strength characterization data





φ' (deg)	21
c' (psf)	750
S_u (tsf)	0.5
DCP blows per ft.	4 to 5

Figure D12: Redwood County site strength characterization data

APPENDIX E: SLOPE STABILIZATION GUIDE FOR MINNESOTA LOCAL GOVERNMENT ENGINEERS

The final project deliverable, the slope stabilization guide, follows. The tool is intended to provide general recommendations for any given slope stabilization issue that public works engineers would encounter in Minnesota, based on researchers' observations from field investigations and LEM modeling results.

INTRODUCTION

This project recommends simple, effective methods of stabilizing at-risk slopes in Minnesota. Slope failures can block roads, pose safety hazards, and introduce preventable maintenance costs. While there is no single stabilization method appropriate for all situations, several methods have proven effective. This project uses slope stability analysis, including limit equilibrium methods (LEM), to investigate recent slope failures in Minnesota. This study provides a consistent, logical approach to slope stabilization that is founded in geotechnical research and experience and applies to common slope failures. This project's end users are public works engineers working on slope stabilization projects. The input for analysis came from Minnesota county engineers.

This guide is the product of a Minnesota Department of Transportation research report: *MnDOT Contract No. 99008, Work Order No. 190, Slope Stabilization and Repair Solutions for Local Government Engineers.* Details, background, and complete descriptions are available in the report. Authors recommend referencing the report when using this guide.

SLOPE FAILURE OVERVIEW

Slope stability is quantified by factor of safety (FS). The FS is the ratio of *in situ* shear strength to the shear strength required for equilibrium along a given potential failure surface. Fundamentally, there are two ways to increase the FS and improve slope stability: introduce stabilizing forces (increase capacity) or limit driving forces (decrease demand). Academic research, standard engineering practice, and worldwide experience have produced many slope stabilization methods; most fit into four categories:

- Limit / manage water in slope material
- Add cover
- Excavate / change slope geometry
- Add support structure

Theoretically, a FS value less than or equal to 1.0 will correspond to slope failure. When slopes fail, visual observation can classify most failures into two types: surficial soil creep or rotational failure. Figure D.1 shows an example of each.

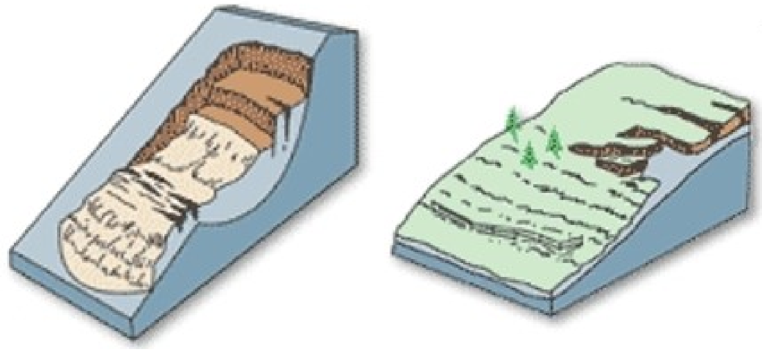


Figure D.1: Examples of common slope failure types (from Varnes, 1978)

Soil type is another important distinction. The two soil types considered are cohesive (i.e silt and clay) and granular (i.e. sand) soils. Visual inspection may distinguish between the two types, but sometimes laboratory testing is required. Sand is typically less likely to exhibit deep rotational slides. Slopes made of cohesive material will have more drainage concerns, and are usually more susceptible to seasonal frost heave.

Water typically has a negative effect on soil's ability to resist shearing, leading to slope instability. An increase in pore pressure (due to water presence) leads to a decrease in effective stress (σ'). Because σ' governs soil strength and deformation characteristics, the presence of water leads to decreased soil shear strength. Groundwater has a significant effect on shear strength, and removing groundwater provided the greatest difference in output FS for each site. The third major site condition distinction is if poor drainage effects the slope. Drainage is considered poor if groundwater lowers soil strength and leads to failure. Cohesive soils, like clay and silt, typically have poor drainage properties. Examples of sites with poor drainage are shown in the site visit summary section of the project report.

SITE CONDITIONS AND SCENARIO DESCRIPTIONS

This guide lays out common slope failure conditions, and provides geotechnical recommendations for stabilization. Based on field observations and the LEM modeling process, researchers developed common site conditions by considering distinctions in three categories: soil type, slope failure type, and presence of groundwater. This led to eight hypothetical scenarios for researchers to make general recommendations.

A flowchart, shown in Figure D.2, helps users determine which scenario to use. The distinction "poor drainage" is interchangeable with "groundwater concerns." Users start at the center, and follow the flowchart outward. Table A.1 provides a summary of the scenarios.

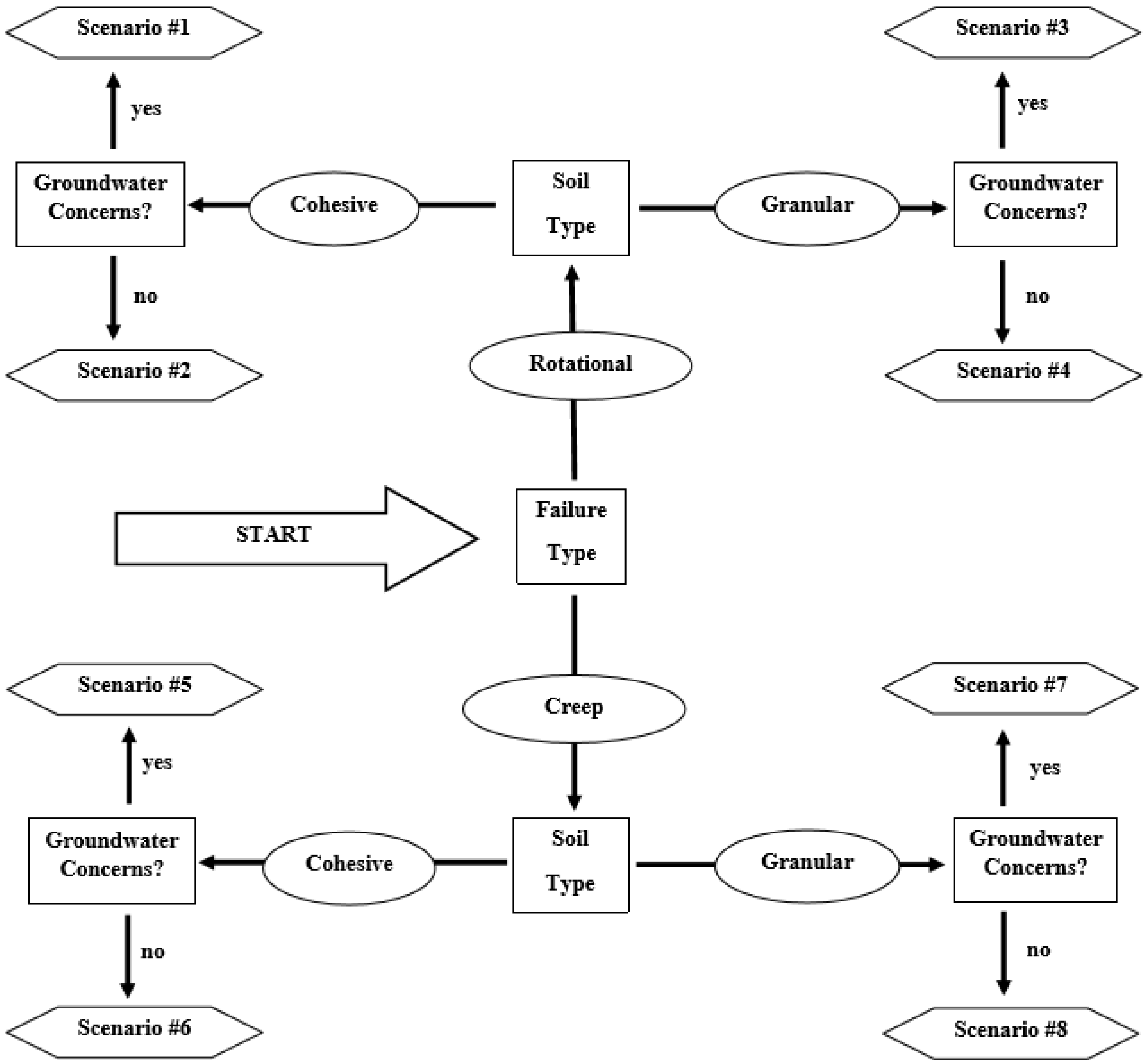


Figure D.2: Flowchart for deliverable scenarios

Table D.1: Deliverable scenarios summary

Name	Failure Type	Soil Type	Groundwater Concerns?
Scenario #1	Rotational Slide	Cohesive	Yes
Scenario #2	Rotational Slide	Cohesive	No
Scenario #3	Rotational Slide	Granular	Yes
Scenario #4	Rotational Slide	Granular	No
Scenario #5	Surficial Creep	Cohesive	Yes
Scenario #6	Surficial Creep	Cohesive	No
Scenario #7	Surficial Creep	Granular	Yes
Scenario #8	Surficial Creep	Granular	No

Table D.2 provides sources for more information on each method that would be recommended. Users can use sources identified to see examples of each method. Researchers recommend viewing the source of background information when selecting a stabilization method.

Table D.2: Sources for more information about each stabilization method

Stabilization Method	Source of Defining Example
Drainage features	Cornforth (2005) Ch. 17
Dewatering	Coduto et al. (2011) Ch. 11
Vegetative cover	Abramson et al. (2002) Ch. 7

Buttressing / rip-rip cover	Abramson et al. (2002) Ch. 7
Geosynthetics	Gee (2015)
Lightweight fill	Abramson et al. (2002) Ch. 7
Remove and replace	Duncan and Wright (2005) Ch. 16
Re-grading and benching	Cornforth (2005) Ch. 15
Retaining walls	Cornforth (2005) Ch. 19
Soil nailing	Abramson et al. (2002) Ch. 7
Mechanically stabilized earth embankments	Abramson et al. (2002) Ch. 7

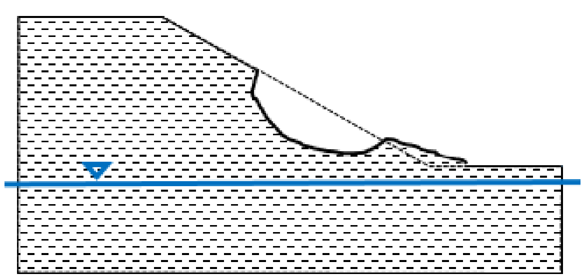
Scenario #1: Rotational failure, cohesive soil, poor drainage

Example of Scenario #1 (from Pennington Co. site)

Recommended stabilization approach:

- Rotational failure
- Cohesive soil
- Groundwater concerns

Remove-and-replace, adding drainage features and vegetative cover

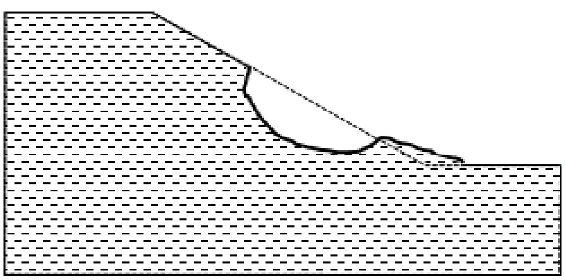


Sites can be identified by visible rotational failure. Maintenance teams should consider either remove-and-replace or regrading with *in situ* soil, adding drainage features, and vegetative cover. Drainage features remove groundwater, and fill-and-regrade work adds stability. Drains should be placed near the toe of the slope. If significant rotational failure has already occurred, the slope will need to be rebuilt. Design teams should consider as low of a slope angle as possible.

Scenario #2: Rotational failure, cohesive soil

Example of Scenario #2 (from Olmsted Co. site)

- Rotational failure
- Cohesive soil
- No groundwater concerns



Recommended stabilization approach:

Remove-and-replace, or regrade and re-compact, with vegetative cover

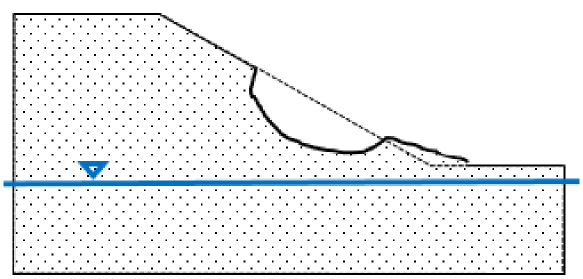
Failure can be identified by visual observation. Many factors can cause soil to lose strength other than groundwater effects, such as poor compaction. Regrading and re-compacting, when properly executed, increases soil strength and slope stability. Maintenance teams should evaluate the *in situ* soil properties, and either re-use the material, or use common borrow if native material has poor properties.

Scenario #3: Rotational failure, granular soil, poor drainage

Rotational failure in sand, similar to Scenario #3

- Rotational failure
- Granular soil
- Groundwater concerns

Remove-and-replace, or re-grade and re-compact, adding drainage features, and adequate surface cover



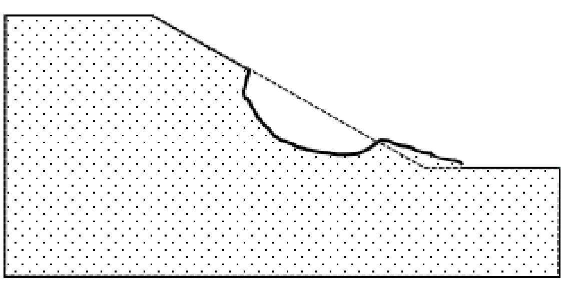
Surface cover is very important for slopes with granular soil because erosion is a concern. Surface erosion can cause geometric inconsistencies lead to failure. Erosion can often cause washout failure. As with other rotational failures, excavation and reconstruction is necessary. Because groundwater is a concern, drainage features are recommended to remove groundwater in the slope. Researchers recommend regrading or, if necessary, replacement with sand fill.

Recommended stabilization approach:

Scenario #4: Rotational failure, granular soil

Example of Scenario #4 (from Lac Qui Parle Co. site

- Rotational failure
- Granular soil
- No groundwater concerns



Regrade and re-compact, with vegetative cover or more involved surface cover

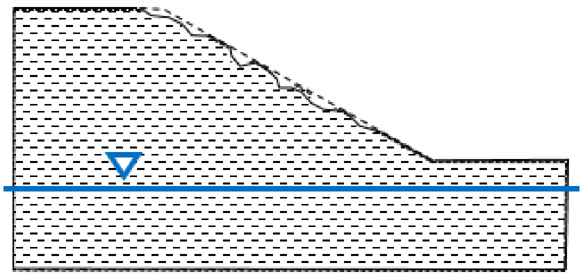
Because groundwater is not the primary reason for failure, the main source of strength loss must be identified and mitigated. If erosion is evident, a more involved cover (i.e. rip rap or gravel) should be considered. Slope steepness may also be a concern. Researchers recommend regrading and compacting with *in situ* material. Extra consideration should be given to adequate ground cover to protect the slope from erosion damage.

Recommended stabilization approach:

Scenario #5: Creep failure, cohesive soil, poor drainage

Example of Scenario #5 (from Koochiching Co. site)

- Creep failure
- Cohesive soil
- Groundwater concerns



Recommended stabilization approach:

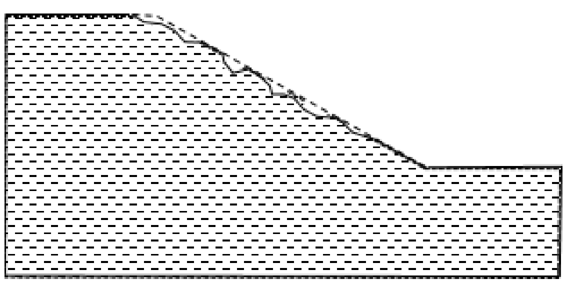
Regrade and re-compact, with drainage features; if one area of failure, remove and replace.

A given site is more likely to have drainage concerns if cohesive material is present. Failure can be identified by crooked signs or trees, and leads to pavement damage. With groundwater present, and *in situ* material being frost-susceptible cohesive soil, frost heave is a possible cause of soil movement. Drainage features are the research team's main recommendation for slope stabilization. If creep is at the top of the slope, maintenance crews can also consider replacing the top portion of the slope with free-draining sand. If the failure is near the bottom of the slope, a buttress can be an effective stabilization method.

Scenario #6: Creep failure, cohesive soil

Example of Scenario #6 (from Murray Co. site)

- Creep failure
- Cohesive soil
- No groundwater concerns



Recommended stabilization approach:

Remove, replace, and re-compact

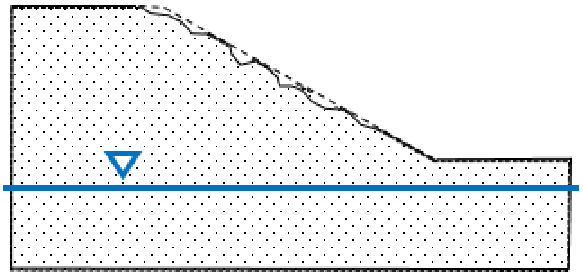
Surface creep can be identified by bio-indicators like bent trees. The example clearly shows how soil creep at the top of a slope can lead to pavement damage. Replacing the failed portion of the slope with sand fill is the recommended option for increasing sliding resistance. In the absence of groundwater, poor compaction decreases the soil's shear strength. If *in situ* soil has adequate strength properties, regrading and re-compaction can be considered, but creep failure indicates concerns about strength of native material.

Scenario #7: Creep failure, granular soil, poor drainage

Example of Scenario #7 (from Carver Co. site)

- Creep failure
- Granular soil
- Groundwater concerns

Remove-and-replace, or re-grade and re-compact, adding drainage features, and adequate surface cover



Adequate ground cover is essential to prevent erosion in slopes with sand. Bent guardrails are evidence of soil creep, which typically causes pavement damage. Proper drainage can remove groundwater from the area, increasing resistance to soil creep. Researchers recommend installing drainage features, and replacing failed soil with properly-compacted fill, or re-compacting *in situ* material. Slope material should be protected from erosion.

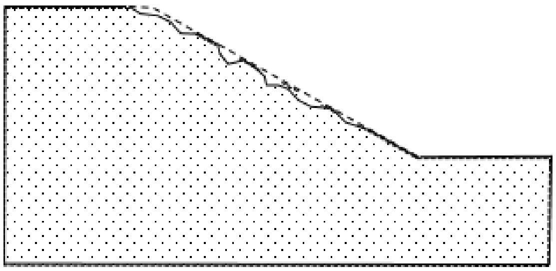
Recommended stabilization approach:

Scenario #8: Creep failure, granular soil

Soil creep in sand, similar to Scenario #8

- Creep failure
- Granular soil
- Groundwater concerns

Remove-and-replace, or re-grade and re-compact, with adequate surface cover



For granular soils, erosion is a concern. Surficial damage caused by erosion is not always soil creep, but the movement type and stabilization attempts are similar. Surface washout can undermine roadways and cause pavement damage. Ensuring adequate ground cover is important when observing surficial damage in slopes with granular fill. Damage at the top of the slope is best repaired by regrading

Recommended stabilization approach: